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LOGISTICS MANAGEMENT INSTITUTE

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to Predict Aircraft Spares Demand

Executive Summary

In Operation Desert Shield/Desert Storm, while tactical aircraft flew much longer sorties than had been anticipated in the war plans, the demand for aircraft spares was substantially less than expected. This expected demand was based on the standard U.S. Air Force assumption that spares demand is proportional to flying hours. Since the Air Force must project wartime demand (for long sorties) from peacetime demand history (from shorter training sorties), it is critical to know whether spares demand is driven by the number of sorties, by flying hours, or by some combination of them.

The Air Force's new war plans for tactical aircraft in the 1993 *USAF War and Mobilization Plan, Volume 5 (WMP-5)* have been updated to longer sortie durations, reflecting the new National Strategy focus on responding to regional contingencies. If the Air Force were to continue to use flying hours as the basis for predicting wartime demand from peacetime experience, the cost of the wartime spares requirement would increase dramatically. We calculated that the gross kit requirements, before subtracting the on-hand spares, would increase by $1.1 billion. Furthermore, the assessments of current capability are too low to be credible using the new WMP-5 and the assumption that demand is proportional to flying hours. As a result, the Air Force imposed a moratorium on using the new plans to compute buy requirements and perform assessments until a solution could be found.

The Air Force has now accepted the results of our analysis, which show that demand is much more closely related to the number of sorties than it is to the number of flying hours. As a result, the overall wartime spares investment requires only modest changes to accommodate the new war plans, although there is substantial reallocation of the investment across items in the kits.

The purpose of this report is to provide the detailed documentation of our analysis. First we review previous research and examine the findings from Operation Desert Shield/Desert Storm. Then, for 24 major aircraft types, we examine operations and maintenance data from the Core Automated Maintenance System (CAMS), in which maintenance actions are related to the characteristics of the preceding sortie — sortie length, mission type, location, etc.

The data comprise over 700 thousand sorties flown from 1993 through 1996, including a number of combat-like sorties in Southwest Asia. While we had hoped to use the Standard Base Supply System (SBSS) for item demand data,

only a small percentage of the SBSS demands could be matched with CAMS maintenance removals. On the other hand, the CAMS maintenance history data did appear to be consistent with the CAMS aircraft utilization data (e.g., for most on-equipment maintenance, the sortie date and number matched). Consequently, instead of demands on supply from SBSS, we used unscheduled maintenance removals from CAMS, selected using criteria making them as close to supply demands as possible. These are the "demands" spoken of in the text.

We describe below — in decreasing order of importance — the four variables that were statistically most significant in explaining demand in any of the data sets and that must be taken into account to assess the impact of sortie length accurately.

Sortie number during the day. When an aircraft flew multiple sorties, the demand rate for the early sorties was only one-third as large as that for the last sortie of the day. The rate for the last sortie was similar to the rate when there was only one sortie during the day. In some cases, the last sortie of the day became the last sortie because of grounding maintenance. But we found evidence that the higher rate occurs primarily because a large amount of maintenance is deferred until after the last sortie of the day.

Mission type. Demands were highest for some of the short training missions that simulate aerial combat. For example, the F-15C/D aircraft pulls as much as 8 Gs on training missions and stresses both pilot and aircraft. On the other hand, some multihour cross-country missions have the lowest demand. Some mission types have three times as many demands per sortie as others. In a regression that does not control for mission type, it is possible to find that demands decrease with sortie duration — an obviously absurd result.

Location. At some A-10 bases, the demand rate was more than five times as large as that at other bases. The smaller demand rates occurred at U.S. Air Force Reserve/Air National Guard bases, not only for the A-10, but for the F-16C/D, HC-130N, and HC-130P as well. In the case of the A-10, the bases with smaller demand rates had slightly shorter sortie durations. If the analysis does not control for different demand rates by location, large and spurious slopes can result.

Sortie duration. The Air Force has been assuming that demand increases linearly with sortie duration — sorties that were twice as long were expected to produce twice as many demands. We find no evidence to support such an assumption. For only 16 of the 24 aircraft types analyzed did we find any statistically significant positive relationship between sortie length and demand. Over the entire data set, the average slope was 12 percent, and that slope dropped to 7 percent when the variable for earlier sorties versus last sortie was included to account for deferred maintenance. (By a slope of 7 percent, we mean that the estimated demand for a 1-hour sortie is increased by 7 percent for each additional hour.) The slope adjusted for earlier/last sortie exceeded 10 percent for only eight aircraft types, including one fighter, one bomber, three transports, and three helicopters. The largest adjusted slope, of 33 percent, still shows a closer relationship to the number of sorties than it does to flying hours. It should be

emphasized that in our analysis we dropped the shortest sorties, which tended to have unusually high demand rates, and the longest sorties, which tended to have unusually low demand rates. This procedure usually increases the slopes and coincides with our objective of giving sortie duration every opportunity to show its influence on demand.

Our recommendation is that the Air Force use a slope of about 10 percent as an overall planning factor, but we have three caveats. First, it is likely that there are some components whose demands have a greater relationship to flying hours than a 10 percent slope. Although the data on any individual item are insufficient to test that hypothesis, we did find larger slopes of 22 percent for fire control and 32 percent for electronic warfare systems on the F-16C and slopes of 19 percent for fire control and 22 percent for electronic warfare systems on the F-15C/D. Also, a slope of, say, 20 percent may be more appropriate for bombers, transports, and helicopters.

The second caveat is that there were only a limited number of long sorties, so that any extrapolation to very long durations is hazardous. Finally, our data were maintenance data, and there is some difference between demands on supply and remove/replace maintenance actions.

In other analyses, demand rates on a particular aircraft did not persist over time, indicating a "lemon" or a "peach," and high demand rates were not correlated with high (or low) utilization. There was a slight increase in demand rates as the number of days between flights increases, but the result was not statistically significant.

The work embodied in this report represents a more comprehensive analysis of the variables that affect unscheduled maintenance removals than does any previous study. Most of the literature is concerned with transport and bomber aircraft, and those studies are over 15 years old. Tactical aircraft are more difficult to analyze, because of the importance of mission type and location. In addition, deferred maintenance is an important phenomenon that has never been considered in earlier studies. If the earlier/last sortie impact is ignored, the effect of sortie duration on demand will be overstated in most cases. Our study benefited greatly from the high quality of the (CAMS/REMIS) Reliability and Maintainability Information System data, the availability of modern database management systems to screen for consistency and facilitate analysis, and the support of many Air Force personnel in designing the study.

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CHAPTER 1

Introduction

PURPOSE

The purpose of the study embodied in this report was to evaluate the impact of sortie duration on spares demand. For many years, the U.S. Air Force has assumed that spares demand is proportional to the number of flying hours, although most of the literature suggests that it is more nearly related to the number of sorties. Of course, when sortie durations are nearly constant, it does not matter whether sorties or flying hours are used, because then they are highly correlated.

Now, as a result of the regional contingency focus of the National Strategy, the planned wartime sortie durations for some aircraft are significantly longer than in peacetime. If wartime demand is projected on a per-sortie basis, the rate is the same as the peacetime rate — but if it is projected on a per-flying-hour basis, the wartime rate will be larger. The impact on requirements may be extremely large.

Our original plan was to run a controlled experiment in which we could measure the impact of sortie duration while controlling for extraneous variation due to such variables as

- aircraft material condition,
- aircrew proficiency,
- mission type,
- location,
- utilization rate, and
- deferred maintenance.

A major reason for conducting a controlled experiment was to ensure that the independent variable of interest — sortie duration — had a sufficient range. During normal peacetime training, variation in the range of sortie durations around the average is limited. But if much longer sortie durations are planned for wartime, it makes sense to collect some peacetime data that relate to longer mission durations.

Another reason for conducting a controlled experiment is that we often gain new insight about a problem during the course of such an experiment. That is one of the reasons why the Air Force conducted the Coronet Warrior exercises, which simulated combat. In particular, a controlled experiment could be very helpful in pinpointing the reasons why we had such difficulty in relating supply data from the Standard Base Supply System (SBSS) to maintenance data from the Core Automated Maintenance System (CAMS).

The Air Force decided not to conduct a controlled experiment, principally because of the additional cost of flying peacetime sorties that are longer than those required for training purposes and the interference with normal operational training. We will not discuss the advantages of a controlled experiment further in the body of this report, but we do show in Appendix A the problems that can arise when explanatory variables are not controlled. In summary, there are many advantages of a controlled experiment, and it may be appropriate to revisit this subject after the results of this study are digested.

Scope of the Report

This report provides a detailed literature review of the impact of sortie duration on spares demand, including a brief summary of Operation Desert Shield/Desert Storm experience. The logic for matching operational and maintenance data from the Reliability and Maintainability Information System (REMIS) is explained, and the in-depth analyses are presented for 24 different aircraft types. Other factors that may influence demand are also explored, such as (1) how the number of days between sorties affects the demand rate, (2) whether high or low demand rates in specific aircraft tend to persist over time, (3) whether there is a correlation between demand and utilization, (4) whether the demand on certain aircraft systems has a greater relationship to flying hours, and (5) whether the higher demand following the last of multiple sorties during a day is due to a grounding condition on that sortie or to deferred maintenance.

A magazine article by Slay, Sherbrooke, and Peterson (1996) summarizes the analyses of REMIS data and presents the impacts for readiness spares kits. It shows how peacetime demand data collected on a flying-hour basis can be *decelerated* to provide better estimates of wartime demand for longer sorties.

Literature Review

Introduction

We present here a summary of the relevant literature, organized by topic heading. After each finding, the authors and year of each study are provided. Appendix C gives a detailed evaluation of the major studies listed here.

It should be remembered that our objective is to relate operations to supply actions. But there is almost no literature of this type. As discussed in the next section, since we were unable to link the operations data with the SBSS data, we carefully defined those maintenance removals that are a reasonable proxy for demands on supply. This was the approach taken in the literature as well.

As a group, the studies generally support the following conclusions:

- Maintenance removals are largely independent of sortie duration.
- Mission type has a large impact on maintenance, particularly for some work unit codes (WUCs).
- Location is an important determinant of maintenance needs.
- Mission-capable rates tend to be higher in deployed exercises than at the home station.
- Higher utilization rates tend to require less maintenance.

The final section presents some quantitative data from earlier studies on the effect of sortie length on unscheduled maintenance removals.

Sortie Duration and Maintenance

- Unscheduled flight-line man-hours are at best only slightly related to sortie length (B-52, F-100, F-102, F-4C [two samples], and F-5A). Only the C-130 showed a fairly constant maintenance-hours (MHs) to flying-hours (FHs) relationship and only for those missions that fly multiple sorties between maintenance stops. [Donaldson and Sweetland, 1968.]
- All maintenance measures were highly correlated with each other — maintenance man-hours, net aircraft recovery time, and number of WUC write-ups. (The latter was always more highly correlated with sortie length, but the absolute difference was small.) Attempts to find relationships between sortie length and maintenance hours by shop were unsuccessful (F-102 sample). [Donaldson and Sweetland, 1968.]
- After 4 hours of a 12-hour B-52 mission, 50 percent of the failures and 47 percent of the abort-causing conditions will have occurred; at 8 hours, the percentages are 80 percent and 93 percent, respectively. [Boeing, 1970.]
- On the B-52, the percentage of components removed to facilitate other maintenance increased with decreased sortie length. [Boeing, 1970.]
- Sortie length and number of landings per sortie have no apparent effect on maintenance man-hours for the C-5. [Little, 1972.]

- The F-4 sortie duration, which varied between 0.8 and 1.8 hours, had little effect on the equipment failure rate per sortie. [Hunsaker et al., 1977.]

- The occurrence of a C-5 sortie tends to result in a given number of maintenance write-ups regardless of the sortie's length. [Casey, 1977.]

- Roughly half of the total maintenance removals per sortie are independent of B-52D sortie length, while the other half are related to sortie duration. In the case of the C-141A, C-130E, and Boeing 727, most of the maintenance removals per sortie depend on sortie length only. This holds true for each major aircraft system as well. [Howell, 1978.]

- The total number of remove-and-replace maintenance removals on the C-5 and C-141 was predicted as well by flying hours as by any other variable (e.g., sorties). Nevertheless, for a few WUCs, other models consistently outperformed this model. [Pederson et al., 1981.]

- The probability of C-141 engine removals is a function of engine age (hours since overhaul) and utilization. As utilization increased, principally as a result of longer sortie durations, demand per flying hour decreased. [Berman et al., 1984.]

Mission Effects and Maintenance

- During a 12-month period, one item of equipment had field mean times between failures (MTBFs) ranging from 107 to 917 hours across six different aircraft types. The MTBFs for avionic equipment on subsonic bombers and transports were 2 to 4 times higher than for similar equipment installed on high-performance tactical or training aircraft. [Kerns and Drnas, 1976.]

- The type of mission flown by the F-4 has a direct impact on the number of maintenance write-ups within specific WUCs. Some WUCs are sensitive to specific types of missions flown. [Hunsaker et al., 1977.]

- In a number of unpublished studies, Sweetland found that maintenance man-hours per sortie decreased considerably below those for training sorties in CONUS. [Donaldson and Sweetland, 1968.]

Location Effects and Maintenance

- Dramatic differences in the number of aircrew-reported malfunctions were found for two bases operating under very similar conditions. In spite of the reported differences, the difference in mission capability, as measured by on-aircraft electronic evaluators, was negligible. Interviews with base maintenance officers indicated that the difference was most likely due to differences in policies concerning malfunction reporting. [Donaldson and Sweetland, 1968.]

- A base-by-base comparison of 3 pieces of equipment on one aircraft type operating from 9 different bases revealed MTBF variations of as much as 5-to-1 from base to base. On average, there was a 2-to-1 difference in reported MTBFs between the 2 best and the 2 worst bases. [Kerns and Drnas, 1976.]

- Hydraulic leaks appear to be related to temperature variations, certain avionics failures to wet climates, and weather radar maintenance to thunderstorm activity. The hydraulic power system on the B-52D is representative of a large class of equipment that has similar removal rates in peacetime and in combat but shows a distinct sortie effect. [Tetmeyer, 1982.]

Material Condition

- The probability of success (no aborts) on specific missions can be enhanced through careful selection of aircraft on the basis of previous maintenance records. Selection should be based on the aircraft's mean performance during two or three preceding quarters, and especially on the reliability of particularly crucial systems during the prior two to five sorties. [McGlothlin, 1964.]

- Mission-capable rates during Coronet Eagle were higher (at 79.4 percent) than at the home station (69.3 percent). Break rates were 7.1 percent versus 12.5 percent respectively at the home base. The highest proportion of breaks came on the first and fourth sorties (8.3 percent and 11.5 percent, respectively). [Coronet Eagle, 1981.]

Data Problems

- The largest single factor contributing to the discrepancy between either predicted or demonstrated MTBFs and field-reported MTBFs was the incorrect use of FHs instead of equipment operating hours (OHs). The OH/FH ratio was 2.0 for the entire database and varied from a relatively insignificant 1.18 to a very significant 2.71, depending on the specific equipment investigated. [Kern and Drnas, 1976.]

- A study should be undertaken to relate maintenance write-ups to actual demands on the wholesale logistics system. No current data system that could track this relationship was found. Hence, a new data collection system would have to be designed specifically for this purpose. [Casey, 1977.]

Utilization Rates

- Total B-52 maintenance man-hours per flight hour decrease as utilization increases and sortie length is held constant. [Boeing, 1970.]

- Aircraft utilization rates (flight hours per month per aircraft) were observed to vary as much as 3 to 1 between different types of aircraft. With military avionics typically operated for only a limited time each month, the non-operating period may be more significant than previously recognized. For one item of equipment, the data indicated that 40 percent of its reported failures had occurred during nonoperational periods. [Kern and Drnas, 1976.]

- Some exercise analyses conducted by the major commands and by RAND suggest that increasing sortie rate has effects similar to the increasing sortie length. [Embry and Crawford, 1983.]

Quantitative Analysis

A number of studies performed through the late 1970s used regression analysis to explain maintenance removals per sortie, Y, as a linear function of the sortie duration in hours, X. Shaw, who performed many of these analyses, chose to express the relationships as a constant term for performing a 1-hour mission plus a variable for the additional maintenance removals per flying hour. His reasoning was that very few missions take less than 1 hour, and that even a takeoff followed by a landing requires some elapsed time. We have adopted this convention for all the regression results in Table 1-1, so that the predictive equations are

$$Y = a + b\,(X - 1),$$

where a and b are the coefficients in Table 1-1, which vary by aircraft. (Note that b is the usual slope obtained from regression, whereas a is the constant term from regression plus b to account for the sortie's first hour.)

Table 1-1.
Regressions of Maintenance Removals on Sortie Duration

Aircraft type	WUC	*a*	*b*	Normalized slope	Number of sorties	Author	Date
C-5A	All	7.74	0.38	0.05	79,181	Shaw	1981
C-5A	Engine	0.50	0.04	0.08	79,181	Shaw	1981
C-141	All	1.38	0.39	0.28	835,000	Shaw	1981
C-141	All	2.18	0.47	0.22	73,000	Shaw	1981
C-141	All	0.90	0.90	1.00	50,388	Howell	1978
C-130E	All	2.05	0.67	0.33	45,000	Shaw, Howell	1981, 1978
P-3C	All	3.60	– 0.02	– 0.01	3,300	Shaw	1981
727	All	0.60	0.46	0.77	54,892	Howell	1978
B-52D	All	12.50	2.50	0.20	10,809	Boeing	1970

It is hard to compare the various aircraft in Table 1-1, because the values for *a* and *b* vary tremendously. Even if we compare the number of maintenance removals for a typical transport sortie of about 4.5 hours, there is a tremendous range from the commercial 727's low value for coefficient *a* to the much higher values for the C-5A and B-52D. In order to compare aircraft with different failure rates, we have divided coefficient *b* by coefficient *a* to obtain a "normalized slope" that is the fractional increase in maintenance removals per additional hour of sortie duration. For example, in the last row of Table 1-1, dividing 2.50 by 12.50 results in a normalized slope of 0.20, which means that for each hour of sortie duration after the first, we would expect a 20 percent increase in the number of unscheduled maintenance removals.[1]

What can we conclude from Table 1-1? All of the normalized slopes are within the range of zero to one (except for the P-3C, whose slightly negative slope is apparently not significantly different statistically from zero, according to a comment by Shaw). A normalized slope of zero indicates that maintenance removals are a function of sorties only, whereas a slope of 1 indicates that they are a function of sortie duration only. Not surprisingly, most of the slopes are between the extremes, with a simple average of about 0.33.

Only two of the normalized slopes suggest that maintenance removals are driven more by flying hours than by sorties: the Howell study for the C-141 and the 727. The Howell results for the C-141 are listed in Table 1-1 after those of Shaw (for 73,000 sorties), which Shaw says are drawn from the Howell data. Yet their regression results are very different, and the numbers of sorties do not agree. (On the other hand, Shaw's results and Howell's results for the C-130E do agree, which is why they are both listed as authors.) The data for the 727 are different from those for the other aircraft; there were only two data points: all commuter flights, averaging 0.566 hours; and all standard flights, averaging 1.32 hours. Since these two data points are quite close together, there is likely to be significant error in estimating the slope. If the two C-141 studies with discrepant results and the 727 study are excluded, the average normalized slope drops to 0.16.

The studies are of only limited relevance to current tactical aircraft, for three major reasons: (1) The average sortie durations are much longer. The sorties of the transport aircraft, except for the 727 as noted above, average about 4.5 hours. The B-52D and P-3C sorties average about 8 hours. (2) Each aircraft was flying only one type of mission, and each mission was unlike a tactical aircraft mission. (3) The data are over 15 years old.

Another problem with data such as these that were not collected in a controlled experiment is that most of the sortie durations are near the average (for instance, 80 percent of the transport sorties are between 3 and 6 hours). The only

[1] Note that this is relative to the baseline, 1-hour rate. The additional 2.5 removals per hour is 20 percent of the 1-hour rate of 12.50 removals. However, the average sortie duration for the B-52D was 8 hours, at which the predicted removals equal 30. The additional 2.50 removals for the 9th hour would only be 8.3 percent of the 8-hour rate. We always calculate the normalized slope relative to the 1-hour rate, to be consistent.

exceptions are the B-52D data, which were collected from three bases flying combat missions in the 1960s. Since the average durations for the three bases were 4, 8, and 11.2 hours, the dispersion was particularly good for studying the impact of sortie duration on maintenance removals.

Desert Storm Experience

During the first 30 days of Desert Storm, the F-15C aircraft stationed at Tabuk flew 236 percent of the planned *WMP-5*[2] flying hours but only 85 percent of the planned sorties. Observed demand per flying hour was much less than forecasted. As shown in Table 1-2, 214 of the items demanded were best forecast using a pure sortie-based forecast and 58 by a pure flying-hour forecast. Similar results were obtained for the F-16C/D. These results are consistent with the literature review and suggest that longer sorties do not result in a proportional increase in demand.

Table 1-2.
Desert Storm Experience

Activity	F-15C	F-16C/D
Desert Storm as a percentage of planned activity		
30-day flying hours	236%	142%
30-day sorties	85%	91%
Forecast accuracy of item demand/flying hour		
Overpredicted by more than 25 percent	84%	81%
Within +/ – 25 percent	7%	10%
Underpredicted by more than 25 percent	9%	9%
Number of items best predicted by		
Flying hours	58	23
Sorties	214	117

[2]The 1993 *USAF War and Mobilization Plan, Volume 5 (WMP-5).*

CHAPTER 2

Matching CAMS and SBSS Data

INTRODUCTION

Our original plan was to link the operational and maintenance information in the Core Automated Maintenance System (CAMS) with the supply data in the Standard Base Supply System (SBSS), because we are interested in relating demands on supply to the sorties during which they occur. While certain maintenance removals are similar to demands on supply, there is always some difference between maintenance and supply data. Furthermore, maintenance data do not provide detailed supply information, such as whether the item is a reparable or a consumable.

DATA DESCRIPTION

We used February 1993 CAMS data for a squadron of F-15C/D aircraft at Langley Air Force Base (AFB), VA. The corresponding SBSS file has 2,781 records, of which 1,791 had aircraft tail numbers. The 990 records without tail numbers are usually demands arising in the back shops, and these were set aside since our principal interest was in relating on-aircraft maintenance to supply. The 1,791 records with aircraft tail numbers were reduced to 430 by a sort for the 24 aircraft from the squadron with CAMS data. Those CAMS records that did not result in a demand would not have a corresponding SBSS record, but for each SBSS record there should be a matching CAMS maintenance record.

MATCH BY EVENT-ID AND TRANSACTION NUMBER

In principle, the simplest way to link data should be to take the transaction number in SBSS and find the matching CAMS Event-ID. But this procedure was unsuccessful; we were able to find a match for only about 10 percent of the 430 SBSS transactions. It was suggested by Langley personnel that this anomaly may be due to post-posting errors when one or more computers are down and the data are entered at a later time. Another possibility is that the tail numbers in the SBSS records are incorrect. (The CAMS tail numbers for maintenance do correspond with the CAMS tail numbers in the aircraft utilization data.) However, a 90 percent error rate for tail numbers in SBSS does not seem credible.

Match by Tail Number

We tried next to use the SBSS tail number and search for the corresponding maintenance history record in the CAMS data for that tail number. In the latter, we were looking for an Install entry and a similar date and part number (the part number is often partially corrupted in SBSS). The date is often different. A later SBSS date makes more sense than vice versa.

Because of partial data corruption, there are problems with computerizing such a process, but even manually we were able to match fewer than one-third of the SBSS transactions.

Match by Part Number

In this case, we did not use the sort on tail number to reduce the number of records. Instead we took the part number from an SBSS transaction and tried to find the matching CAMS maintenance record. Using SBSS part number or nomenclature (e.g., Control, Engine), we were even less successful than with the two other methods we have described. Nomenclature is particularly poor, because it may be spaced or abbreviated differently in CAMS. When one uses something like **main tire**, there is a tremendous amount of useless information concerning **discrepancy**, **corrective action**, and other maintenance categories.

In some cases, there was no match at all, even when the part number appeared several times in SBSS (e.g., 4060542). At other times, there was a match but with a different tail number and a wildly different date. Again, it seems likely that matching this way will require a great deal of judgment.

CHAPTER 3

CAMS Logic for Matching Maintenance and Sorties

INTRODUCTION

Our immediate objective is to extract from the maintenance history data in CAMS those maintenance removals that most closely approximate spares demand and relate those maintenance removals to the sorties during which they occurred (using the CAMS Daily Report of sorties by tail number). The ultimate goal is to determine the factors that drive spares demand. They include sortie duration, but also mission type, location, and sortie number during the day (since some maintenance is deferred until after the last sortie of the day). CAMS feeds REMIS, and because the latter is maintained centrally by the Air Force, we used its data for most worldwide analyses. The alternative would have been to collect CAMS data individually from each base. The CAMS data call that went to the Air Force is shown in Appendix D.

MAINTENANCE HISTORY

The maintenance history records of interest are those for on-aircraft remove and replace, excluding cannibalizations or those remove-and-replace actions performed to facilitate access to other items. We selected only those maintenance removals with the following Action Taken codes:

- *P — Item is removed.* Additional actions (later installation) will be accounted for separately (on-equipment only).
- *R — Remove and replace* (on-equipment only).

We did not include Q-coded actions (item installed only — separate action for removal — not for cannibalization or access), because there must have been a separate, earlier event for the removal, which would have been picked up with the P code. It was suggested that we might want to use code Q (reinstall only) for job control numbers without a P (remove only), but we do not want to count both. However, it is more difficult to relate sortie numbers and dates for these Q

actions, and there appear to be few of them without a corresponding P. (None of the U.S. Air Force, Europe (USAFE), records were Qs, and only 122 of 3,414 Langley records were Qs.)[1]

We further reduced the maintenance history records of interest by excluding maintenance removals with How Malfunctioned codes of 793 – 812 or 911, which are No Defect codes. There is a field for units produced. A value of zero is used to indicate an adjustment, so only records with a value of 1 or more are retained.

We excluded WUCs 01 through 09 because they are aircraft servicing codes, and we excluded Technical Order Compliance Actions because they are not due to activities from the previous sortie. We excluded Time Change items as well, since they depend on the number of hours or sorties and not on the activity from the previous sortie. Our processing logic automatically excludes them anyway, because the How Malfunctioned code is a No Defect code, and we automatically excluded those.

Calculating Dates and Times

The CAMS Daily Report of aircraft utilization contains both a Julian date and a calendar date. In some cases there is a discrepancy of a day because the calendar date and time have been converted to Zulu (Greenwich Mean Time). We used the latter but had to convert to local time at each site because the maintenance records are kept in local time.

The maintenance records contain Julian and calendar date also. The Julian date is supposed to be the *when discovered* date, while the calendar date and start time are when the maintenance action commenced. In most records, the Julian date is the same as or earlier than the calendar date, but there are exceptions. Therefore, we used the following logic to determine the when discovered date and time:

1. Julian date same as calendar date — use start time from the record.

2. Julian date earlier than calendar date — use Julian date and start time of 23:59 if the difference is less than or equal to 30 days.

3. Julian date earlier than calendar date — discard the record if the difference is more than 30 days.

4. Julian date later than calendar date — use calendar date and time.

The 23:59 start time ensures that in the matching process, the maintenance action will be matched with the last sortie of the day (or of a previous day if there was no sortie that day). The logic in case 3 is that there was probably an error in the

[1] Originally we analyzed some USAFE data for the F-15C/D. They did not contain location information. A later REMIS data set included location for all F-15C/D aircraft worldwide, and so it was used instead.

Julian conversion, since the maintenance cannot begin (calendar time) before the need for it is discovered (Julian).

For example, on the AC-130 maintenance history records, this logic led to the following number of records in the four respective cases: 1,769, 3,059, 293, and 265. Adding all cases, except the third, there were a total of 5,093 maintenance records retained. Using smaller values for the number of days in case 2 leads to fewer records, of course. Instead of 3,059 in case 2, we get 2,606 when the number of days = 10, and 1,783 when the number of days = 2. We used the longer 30-day window, even though there are sometimes other sorties during the period, because these are remove-and-replace actions that may be delayed for lack of a spare. Presumably these are not items that are critical to mission worthiness.

Linking Maintenance History to the CAMS Daily Report

To facilitate future analysis, we entered all flights into a FOXPRO database. For each flight, we entered the following data from the CAMS Daily Report:

- Tail number
- Date
- Sortie number (3-digit code)
- Start time
- Sortie duration (in tenths of an hour).

We then used the maintenance history files as extracted above to enter the number of demands arising from each sortie. This involved matching the sortie number (if present in the maintenance history record and provided that the when discovered code is either a D — in flight, or E — post-flight). If the when discovered code is A, B, or J — before flight, we attempted to find the previous flight of the same tail number to record the demand.

When discovered code C indicates an air abort. Those sorties were eliminated because the sortie time is likely to have been reduced (there were 2 air aborts in 865 maintenance removals for USAFE and 16 in 3,414 for Langley). However, there are likely to be some additional sorties that were shortened because of maintenance that are not coded C. Coding an air abort is a judgment call by the operations people, who may feel that the mission performed all the actions required even though it was shortened.

When discovered code K, M, or Q records were excluded because they are hourly post-flight or special inspections that are not usually related to the activity during the previous sortie. There were only a small number of these.

The procedure is more complicated when the sortie number is not provided (more than half the cases in the Langley CAMS maintenance data and all the REMIS data). If no sortie took place on the day of a demand, we assigned the demand to the last sortie flown on a previous day. when there were sorties during the day, the when discovered time is used to assign the maintenance to the previous sortie.

A given WUC normally indicates a specific master item in an interchangeable and substitutable group. For a given mission design series (MDS), it has a unique meaning (does not change from one location to another). Most but not all of the WUCs are for reparable items. However, some items do not have a WUC (typically the less important ones). Also, there is a catchall WUC in which the last two digits are 99, meaning "not otherwise coded" (these are likely to be for consumables; there were only 113 of them in the 3,414 Langley records and only 48 in the 865 USAFE records). There is supposedly a code TO33K that is a cross-reference between the national stock number (NSN) and WUC. Using it would appear to be the best way to separate reparables from consumables in the maintenance data.

Demand Rates

The demand rates that we calculate should be reasonably accurate. In some cases there are sorties for tail numbers that never show any maintenance actions. These sorties are dropped on the assumption that the maintenance records are missing. Maintenance actions that cannot be matched to sorties are dropped, as well.

However, there is no guarantee that the remaining sorties and maintenance actions are a complete set. On the other hand, it is reasonable to assume that any random set of missing sorties or maintenance actions will not markedly offset the slope of demand versus sortie length. This stability has been observed when sorties for tail numbers with no maintenance have been dropped.

CHAPTER 4

Analysis of CAMS and REMIS Data — Fighter Aircraft

INTRODUCTION

In the preceding chapters, we detailed our attempts to tie supply data from SBSS to maintenance data from CAMS and have shown that we were unable to do so. Therefore, this chapter will instead use removals from CAMS and from REMIS. These will be selected so as to permit them to serve as approximations of or surrogates for demands on supply. For simplicity's sake, we term these unscheduled maintenance actions "demands." The CAMS and REMIS data analyzed here are for a number of different aircraft.

Our principal concern is to examine the impact of sortie duration on demand. The analyses that follow show that variables other than sortie duration are more important in predicting demand. These include only or last sortie of the day versus earlier sorties of multiple sorties, mission type, and location. We used both simple and multiple regressions on the individual sortie data. (Appendix B explains why it is inappropriate to analyze aggregated sortie data.)

For most aircraft types analyzed, the demands from the last of multiple sorties during a day are about three times as large as the demands from earlier sorties. Sometimes this situation occurs because the number or types of demands prevent the operators from flying another sortie with that aircraft on that day, in which case the sortie becomes the last one of the day. But, on the basis of evidence presented in Chapter 11, we believe that the higher demand rate following the last sortie of the day is primarily due to deferred maintenance.

Deferred maintenance also explains why demands tend to be lower when an aircraft deploys to another location and higher when it returns to its home station. It is important to understand these effects and take them into account to obtain a correct estimate for the impact of sortie duration on demand.

In Chapters 5 through 9, we consider other types of aircraft: attack, bombers, reconnaissance, transports/tankers/special operations forces (SOF), and helicopters. Chapter 10 contains a summary of all aircraft analyzed.

Langley F-15C/D Using CAMS

This is an analysis of the CAMS data received from Langley for the period from 1 January through late September 1993 for Langley's F-15C/Ds. We excluded the 12 tail numbers that deployed to Southwest Asia in the May – June period because they are analyzed separately below with a larger data set obtained from REMIS.

For the remaining 68 aircraft, we discovered that the demands after the only sortie of the day were the highest. When multiple sorties were flown during a day, the demands tended to decline slightly with each succeeding sortie, except that after the last sortie of the day, the rate was almost as high as for an only sortie of the day. (See Table 4-1.) We interpret this result as reflecting the fact that there is some maintenance that can be deferred until after the last sortie of the day. When maintenance cannot be deferred, that forces the sortie to be the last (or only) sortie of the day.

Table 4-1.
Impact of Sortie Number on Demand

Sortie number of the day	Number of sorties	Average length (hours)	Demands/sortie
Only	1,857	1.54	0.62
1 of multiple	2,804	1.35	0.17
2 of multiple	796	1.22	0.14
3 of multiple	418	1.15	0.12
4 of multiple	178	1.12	0.10
5 of multiple	45	1.00	0.11
6 of multiple	1	0.90	0.00
Last of multiple	2,820	1.33	0.52
Total/average	8,919	1.36	0.37

Note: In some tables, the number of first and last sorties of multiple sorties is slightly different, because after determining the sortie number during the day some sorties were excluded for analysis due to air aborts or other causes. This is because we are attempting to predict demand as a function of planned sortie duration, and we know these air aborts have sortie durations that have been altered. Also in some tables of demand rates by location, the sorties do not add to the total because some locations with few sorties are not listed.

We noticed some large differences in demand depending on the mission type, as shown in Table 4-2. The T3GA missions are aerial combat training sorties, during which the aircraft may pull as much as 8 Gs. T3XAs are cross-country training missions, which tend to be longer and less stressful. T3LAs are training deployment missions. The higher demand rates are associated with the shorter sorties, but this occurs because of the importance of mission type.

Table 4-2.
Impact of Mission Type on Demand

Mission type	Number of sorties	Average length (hours)	Demands/sortie
T3GA	7,247	1.32	0.39
T3LA	498	1.47	0.15
T3XA	973	1.64	0.27
Miscellaneous	201	1.23	0.56
Total	8,919	1.36	0.37

Our Langley CAMS data included sortie takeoff and landing locations. We noticed that when aircraft went from Langley to somewhere else, the maintenance was lowest (indicating some deferrals), and that when aircraft returned to Langley from somewhere else, the rate was highest. Unfortunately, the REMIS data used elsewhere in this report do not include landing location, but the overall results are affected only slightly, since only 5 percent of the sorties involved other locations. Furthermore, most of the sorties in the last two rows of Table 4-3 were T3LA and T3XA missions. Although there were only 55 T3GA missions in the last two rows, the demands per sortie for them were very comparable (at 0.41 and 0.48) to the 0.39 demands per sortie for T3GA missions in Table 4-2. Thus, if we control for mission type in our analyses, the results for the T3GA missions are affected only slightly by takeoff and landing location.

Table 4-3.
Impact of Location on Demand (Langley F-15C/D Using CAMS)

Takeoff and landing locations	Number of sorties	Average length (hours)	Demands/sortie
Langley to Langley	7,173	1.30	0.40
Not Langley to Langley	224	2.04	0.66
Langley to Not Langley	184	2.21	0.16

We analyzed, as a group, the 7,108 T3GA missions that took off and landed at Langley. This group comprises most of the sorties in the data, and using it eliminates the impact of mission type and location. The data for demands versus sortie duration are plotted in Figure 4-1, where each X represents the average number of demands for all sorties of that duration. The purpose of this graph is to give the reader some insight into the relationship between sortie duration and demand. However, Figure 4-1 provides an imperfect picture of that relationship. Not all durations had the same number of sorties. Thus, some Xs represent only a single sortie while others represent the average of a large number of sorties. When fitting a regression line through these points, it is essential to weigh each point by its number of sorties. Unfortunately, there is no effective way to represent visually the number of sorties at each duration.

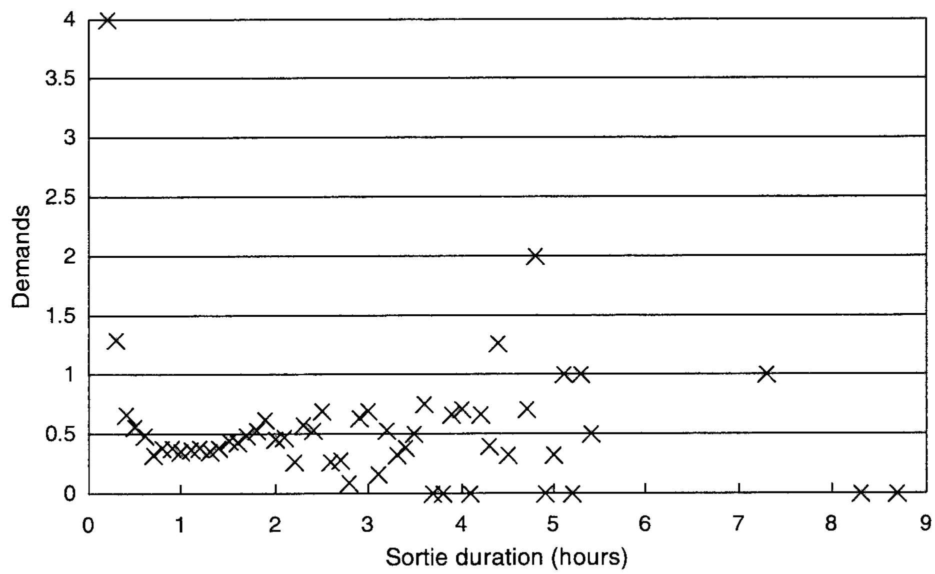

Figure 4-1.
Langley F-15C/D in 1993; 7,108 T3GA Roundtrips

For this reason, we combined neighboring data points with small sample sizes to obtain Figure 4-2. Thus the high demand rates of 4 and 2 at 0.2 hours and 4.8 hours, respectively, in Figure 4-1 — each of which is computed from a single sortie — are combined with neighbors. Similarly, the demand rates of zero at 8.3 and 8.7 hours, which also came from single sorties, are combined with neighbors. On the other hand, the demand rate of 0.37 at 1.1 hours, computed from 1,031 sorties, appears in both figures. It is much easier to "eyeball" the regression line from the graph of Figure 4-2. However, the statistical significance of the regression cannot be ascertained from Figure 4-2, because it depends on the scatter of the individual sortie data, as explained in Appendix B.

We note that one of the highest demand rates in Figure 4-2 is at the lowest sortie duration, which combines all 177 sorties of up to 0.7 hours. Now, it is unlikely that a pilot can accomplish all of the planned activities of a T3GA mission in such a short time. Even including these short sorties, T3GA missions average 1.32 hours. It is likely that the planned duration of most of these short sorties was substantially greater than 0.7 hours and that at least some of them were terminated earlier for maintenance reasons. As described in Chapter 3, we excluded all sorties coded Air Abort. However, as we mentioned, this is a judgment call by the pilot, and sometimes a sortie is terminated earlier but not coded Air Abort because most of the planned activities were accomplished.

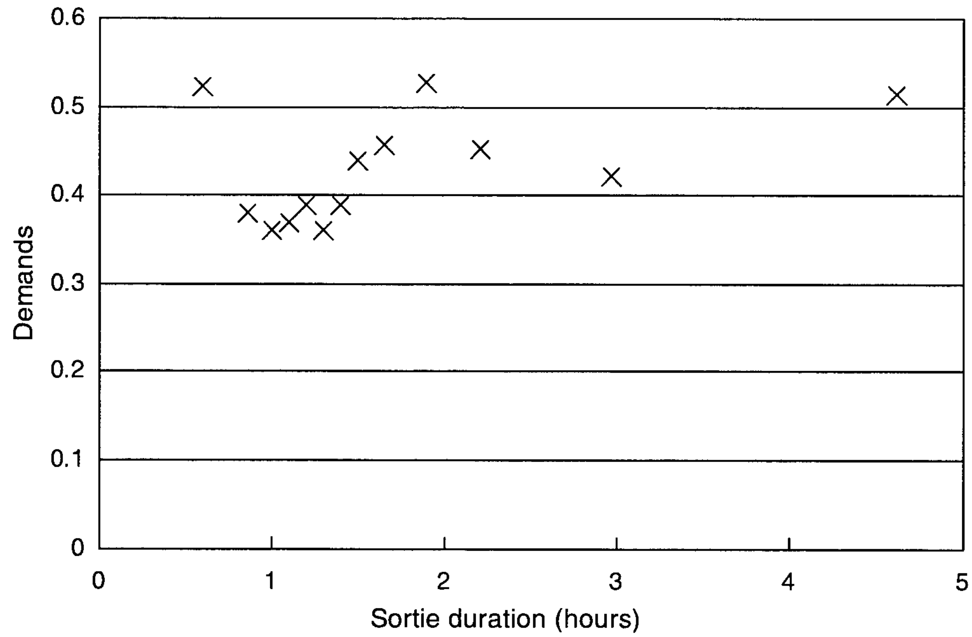

Figure 4-2.
Langley F-15C/D in 1993; 7,108 T3GA Roundtrips (Aggregated)

In such cases, where there is some ambiguity, we want to make decisions that give sortie duration the benefit of the doubt when judging its impact on demand. That is, by excluding the high-demand-rate short sorties from the regression, we will obtain a regression in which sortie duration has a greater positive slope. But we will find at the conclusion of our analyses that even giving sortie duration the benefit of any doubt, the result remains that sortie duration has only a modest impact on demand.

The resulting regression was for sortie durations between 0.7 and 7.3 hours; it includes 7,020 sorties. The regression has a slope of about 18 percent and is statistically significant at the 95 percent level (i.e., there is less than a 5 percent chance that such a large slope could have been caused by chance instead of by a real relation between sortie duration and demand).

As noted earlier in our discussion of Table 4-1, the impact of only/last sortie versus earlier sortie is very large. It is statistically more significant than sortie duration even after short sorties are eliminated. Now the evidence set forth at the end of Chapter 11 suggests that most of the difference between demand rates from earlier sorties of the day and those of the last sortie of the day results from deferred maintenance. Thus, the demand rate after earlier sorties is understated, while the demand rate after the last sortie is overstated. Since we are trying to relate the actual demand to each sortie, we will define an earlier/last sortie variable that assumes a value of -1 on the earlier sorties, a value of 1 on the last of multiple sorties, and a value of zero on the only sortie of the day. We will estimate the magnitude of deferred maintenance by regression, where we are

assuming that the amount of overstatement on the last sortie equals the combined amount of understatement on earlier sorties.[1]

When the variables for earlier/last sortie and sortie duration are used together as independent variables in a multiple regression, the slope for demand as a function of sortie duration drops to 13 percent and is still statistically significant. The slope is smaller because the last sortie of the day, which has more demand, tends to be slightly longer, as can be seen in Table 4-1.

One limitation in this data set is that most of the sorties are near the average duration of 1.36 hours. The 7,020 sorties used in the regressions include only 62 that are 3.7 hours or longer, and only 121 that are between 2.5 and 3.6 hours. Longer sortie durations are important, because we are trying to estimate demand rates for them and because they have a greater influence on the slope of the regression line.

Langley F-15C/D in Area of Responsibility Using CAMS and REMIS Data

This section compares the CAMS data received from Langley for its F-15C/Ds in the area of responsibility (AOR) of Southwest Asia from mid-June through 30 September 1993 with the REMIS data from mid-June to year-end. We have already discovered that the REMIS data agree with the Langley data and can be used. However, we found that the sortie start times in the REMIS data are in Greenwich Mean Time (Zulu), so that 3 hours must be added to make the start times comparable with the maintenance times, which are in local time. (We converted sorties to local time at each location for all REMIS data described in the following sections.)

The REMIS set contains about twice as much data as the CAMS set. The A7VA air combat patrol missions have about the same demand rates in each set, as shown in Table 4-4. Because we excluded all T3GA training on each aircraft prior to its first combat mission, the T3GA missions have a much lower rate in the REMIS data. This training was excluded to eliminate maintenance that may have been generated during the deployment to Dhahran, Saudi Arabia, and deferred until arrival. Because there are so few T3GA missions for these aircraft, we will not analyze them.

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[1] A more precise analysis might take into account that for every last sortie of multiple sorties there are an average of 1.55 earlier sorties. Thus if the value of 1 is retained for the last sortie, a value of – 0.65 would be appropriate for an earlier sortie. This would increase the slope adjusted for earlier/last sortie to 15 percent. However, the constant would have to be determined separately for each data set.

Table 4-4.
Comparison of CAMS and REMIS Data (Langley F-15C/D in AOR)

	CAMS	REMIS
Sorties – total	671	1,361
T3GA	141	124
A7VA	530	1,237
Demands/sortie – average	0.36	0.31
T3GA	0.49	0.16
A7VA	0.32	0.33
Sortie length (hours)		
T3GA	3.29	1.60
A7VA	2.98	3.26

In a further attempt to understand what was really occurring, we broke the REMIS data into three periods, each having about the same number of sorties. Table 4-5 is the result. The column headings are the Julian dates. We see a large reduction over time in demands per sortie for the combat air patrol (A7VA) missions.

Table 4-5.
Changes by Time Period (Julian Dates)

	93213 – 93249	93250 – 93309	93310 – 93365
T3GA sorties	0	40	84
A7VA sorties	335	517	385
T3GA demands/sortie	–	0.13	0.18
A7VA demands/sortie	0.43	0.33	0.23
T3GA sortie length (hours)	–	1.57	1.61
A7VA sortie length (hours)	3.04	3.30	3.40

As in every other data set, the demand after the only sortie of the day was higher than after the earlier sorties of multiple sorties, as shown in Table 4-6. However, in contrast with every other data set not concerned with Southwest Asia, the demand rate after the last of multiple sorties was quite low. Our interpretation is that there was less deferred maintenance in Dhahran than in the United States, because of the wartime mission type. This notion is reinforced by the fact that the demand rates by sortie number vary less than in other data sets.

Table 4-6.
Impact of Sortie Number on Demand (Langley F-15C/D in AOR)

Sortie number of the day	Number of sorties	Average length (hours)	Demands/sortie
Only	562	3.31	0.42
1 of multiple	321	3.29	0.29
2 of multiple	33	2.91	0.18
Last of multiple	321	3.19	0.21
Total/average	1,237	3.26	0.33

Another difference from other locations is that the A7VA sorties were flown around the clock, as shown in Table 4-7. Though there was a decrease in the number of early-morning takeoffs, we modified the logic for matching maintenance to sorties because of the large amount of nighttime flying. Instead of requiring that maintenance must begin on the same day or on the following day to be matched to the sortie, we allowed an extra day. Though one would expect that maintenance would be expedited in these combat-like circumstances, the utilization rate was only 1.18 sorties per aircraft per day.

Table 4-7.
A7VA Sorties by Hour of the Day (Langley F-15C/D in AOR)

Time	0000-0400	0400-0800	0800-1200	1200-1600	1600-2000	2000-2400	Total
Number of sorties	81	258	299	236	207	156	1,237

The data for the 1,237 A7VA missions are plotted in Figures 4-3 and 4-4. Again, it is difficult to determine the "best fit" from the detail data in Figure 4-3, because the high demand values tend to be associated with small numbers of sorties. When the data are aggregated in Figure 4-4, we see a high demand rate for the shortest sortie durations. Using the same logic as in the previous section to give demands as a function of sortie duration every chance to have a positive slope, we retained the 1,178 sorties with durations between 1.0 and 4.1 hours. Doing so results in a 9 percent slope, but the slope is not statistically significant.

When the variable for earlier/last sortie is included in a multiple regression, the resulting slope is still 9 percent and it is still not statistically significant. This result is not surprising, because Table 4-6 shows very little variation in sortie length as a function of sortie number during the day.

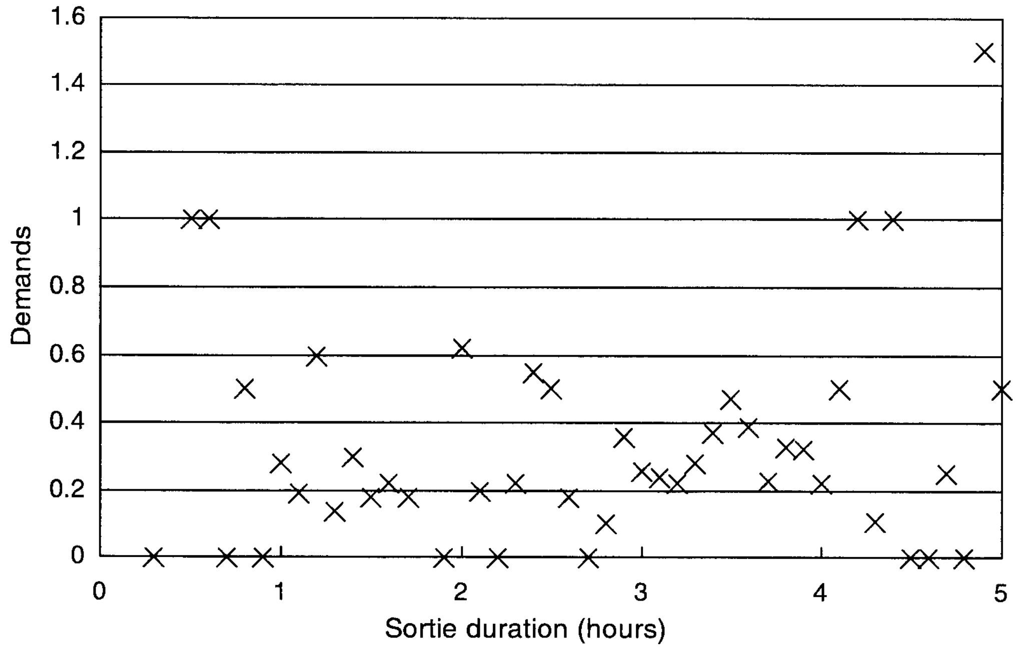

Figure 4-3.
AOR F-15C/D in 1993; 1,237 A7VA Missions

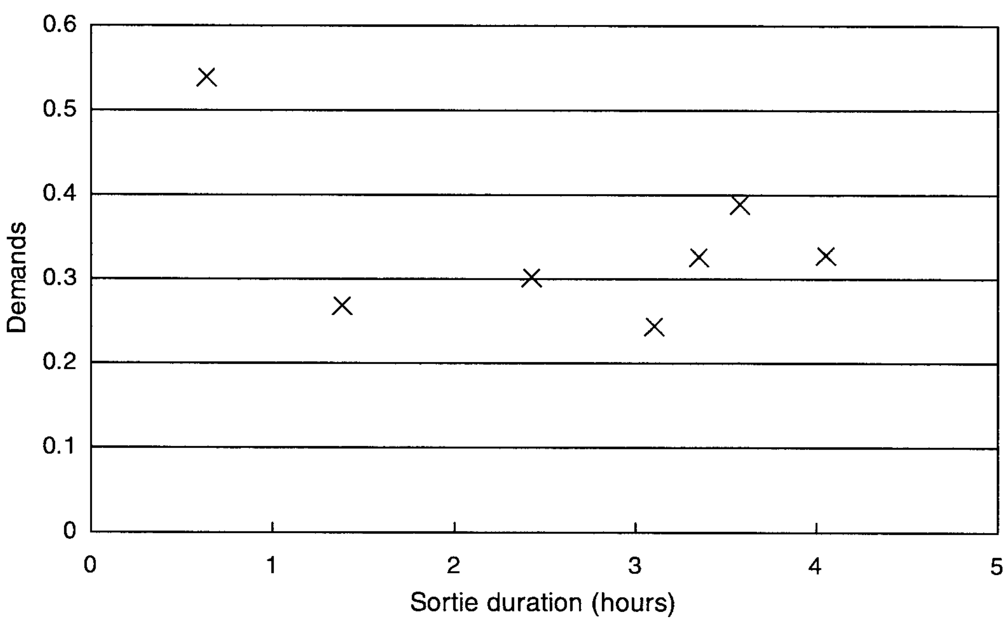

Figure 4-4.
AOR F-15C/D in 1993; 1,237 A7VA Missions (Aggregated)

Although the AOR data set has fewer sorties than the Langley data discussed in the previous section, it does have the advantage that the average sortie duration of 3.26 hours is much longer than the Langley average of 1.36 hours for T3GA missions. Thus, it is more relevant to the problem of predicting demand on long sorties. It is interesting to note that the overall average demand per sortie of 0.33 on the longer A7VA missions is slightly lower than the rate of 0.39 on the stateside T3GA missions of Table 4-2. This is not surprising, because combat air patrol is likely to put less stress on the aircraft than T3GA missions with 8G turns.

F-15C/D Worldwide in 1993

This is an analysis of the worldwide REMIS data from about May 1993 through the end of that year. Again, the most important predictor of demand was the sortie number, where demands after the only/last sortie of the day were much higher, as seen in Table 4-8. It is interesting to note that although demands per sortie were similar for the only sortie and for the last sortie, the duration of the latter was a good deal less — about the same as for the first of multiple sorties. This fact is another illustration that sortie number during the day has a greater impact on the demand rate than does sortie duration.

Table 4-8.
Impact of Sortie Number on Demand (F-15C/D Worldwide in 1993)

Sortie number of the day	Number of sorties	Average length (hours)	Demands/sortie
Only	7,706	1.81	0.68
1 of multiple	8,136	1.40	0.19
2 of multiple	1,921	1.20	0.16
3 of multiple	512	1.10	0.13
4 of multiple	188	1.02	0.10
5 of multiple	53	0.89	0.09
6 of multiple	1	0.90	0.00
Last of multiple	8,135	1.38	0.70
Total/average	26,652	1.49	0.48

The demand rates varied slightly by location, as shown in Table 4-9. The values shown in Table 4-9 exclude the A7VA combat missions flown in the Southwest Asia AOR by Langley aircraft, because they were analyzed in the previous section. Those locations with higher demand rates do not show any pattern with regard to sortie length.

We analyzed the data in Table 4-9 several ways. First, a regression for the entire group of 26,652 sorties was performed. Then we did separate analyses for locations such as Kadena and Elmendorf, where there were large numbers of sorties of a single mission type. Finally, we performed an analysis for the group

of training missions worldwide (T2D, T3D, T3G, T2O, T3O, T20, T30, and T3Q). We dropped the 57 sorties of 0.5 hours or less, which had a large demand rate of 0.79, and the 161 sorties longer than 5 hours, which had a small demand rate of 0.30. The 16,522 remaining sorties do not show a positive slope, either before or after the adjustment for earlier versus last of multiple sorties.

Table 4-9.
Sorties and Demand Rates by Location (F-15C/D Worldwide in 1993)

Location	Total sorties	Average length (hours)	Demands/sortie
Eglin, FL	1,176	1.29	0.53
Keflavik, Iceland	1,255	1.60	0.51
Elmendorf, AK	4,851	1.53	0.51
Tyndall, FL	4,475	1.28	0.51
Kadena, Okinawa	6,307	1.51	0.50
Mountain Home, ID	120	1.76	0.46
Bitburg, Germany	3,055	2.04	0.45
Langley, VA	3,822	1.35	0.42
Edwards, CA	80	1.82	0.41
Nellis, NV	1,509	1.14	0.39
Total/average	26,652	1.49	0.48

F-15C/D Worldwide in 1994

This is an analysis of the worldwide REMIS data for the first 6 months of 1994. Demand after the only sortie of the day or after the last of multiple sorties was again much higher than demand after earlier sorties of multiple sorties. The results in Table 4-10 are almost identical to those in Table 4-8 for 1993. The demand by location is very similar to that in Table 4-9, so we have not displayed it here.

We selected the 709 A7VA missions flown in the Southwest Asia AOR in this data set for special analysis as in our earlier A7VA analysis, because the sorties are longer, the location does not vary, and there is less of a problem with deferred maintenance in these combat-like missions. Figures 4-5 and 4-6 are plots of the data. However, even excluding the short sorties of less than an hour, the slope of demand as a function of sortie duration is not positive.

Table 4-10.
Impact of Sortie Number on Demand (F-15C/D Worldwide in 1994)

Sortie number of the day	Number of sorties	Average length (hours)	Demands/sortie
Only	6,923	1.85	0.70
1 of multiple	6,899	1.39	0.19
2 of multiple	1,603	1.23	0.16
3 of multiple	545	1.11	0.14
4 of multiple	175	0.99	0.17
5 of multiple	33	0.88	0.09
Last	6,899	1.40	0.67
Total/average	23,077	1.51	0.48

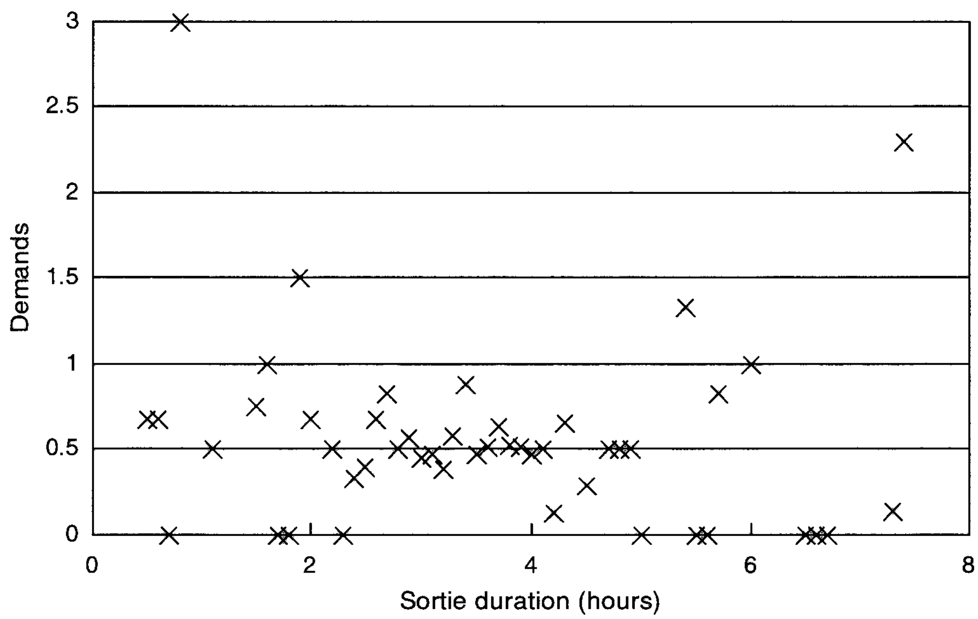

Figure 4-5.
AOR F-15C/D in 1994; 709 A7VA Missions

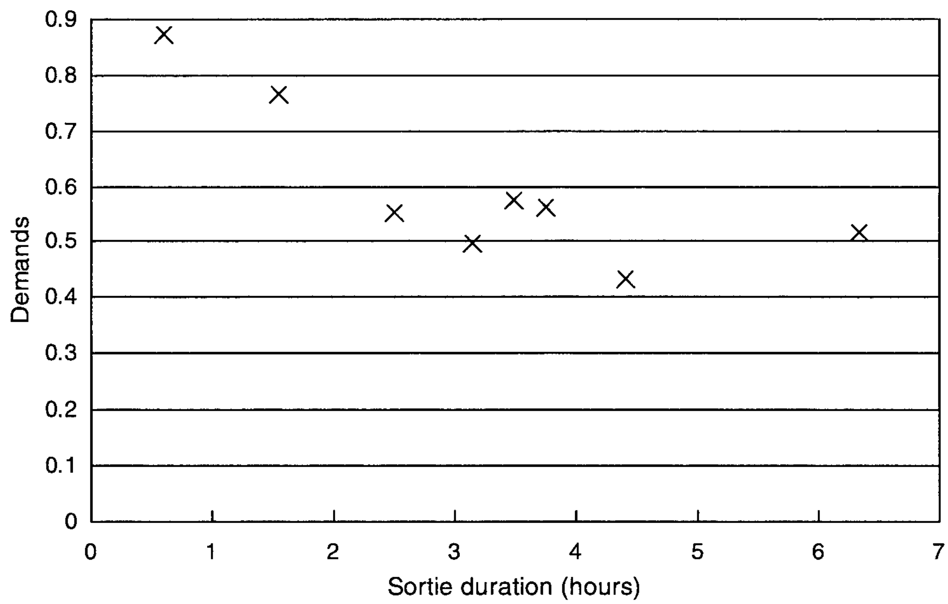

Figure 4-6.
AOR F-15C/D in 1994; 709 A7VA Missions (Aggregated)

The 8,303 T3GA missions between 0.9 and 2.5 hours flown from all bases were analyzed as group. There was a statistically nonsignificant 2 percent slope for these, which disappeared when the variable for earlier/last sortie was included. Lastly, we performed an analysis for the group of training missions worldwide (T2D, T3D, T3G, T2O, T3O, T20, T30, and T3Q). We dropped the 163 sorties of 0.6 hours or less, which had a large demand rate of 0.72, and the 112 sorties longer than 5 hours, which had a small demand rate of 0.34. The 15,514 remaining sorties do not show a positive slope, either before or after the adjustment for earlier versus last of multiple sorties in a day. Other analyses for bases with large numbers of sorties failed to give any positive slopes.

F-15C/D Worldwide in 1995

A similar analysis was performed on the worldwide REMIS data for the first 6 months of 1995. The distribution of sorties per day is not shown because it is very close to Table 4-10 as are the average sortie duration of 1.56 hours and the average demand per sortie of 0.46. We retained the same training sorties as above with durations between 0.9 and 4 hours. The 20,329 sorties do not show a positive slope, either before or after the adjustment for earlier versus last of multiple sorties in a day.

F-16C Worldwide in 1994

There were 99,994 F-16C sorties worldwide in our REMIS database covering the first 7 months of 1994. Two subsets of these data were selected for special analysis.

The A7LA missions in this data set represent missions in the AOR. As with the A7VA missions for the F-15C/D, these A7LA missions tend to be longer than the training sorties in any location and thus are particularly relevant to our problem of predicting the impact of sortie duration on demand. After we dropped the 10 sorties of 0.7 hours or less with a high demand rate of 0.40 and the 15 sorties of more than 10 hours with a low demand rate of 0.07, the remaining 1,718 sorties were analyzed; the results are displayed in Figures 4-7 and 4-8. The slopes are statistically nonsignificant at 10 percent both before and after adjustment for earlier/last sortie duration.

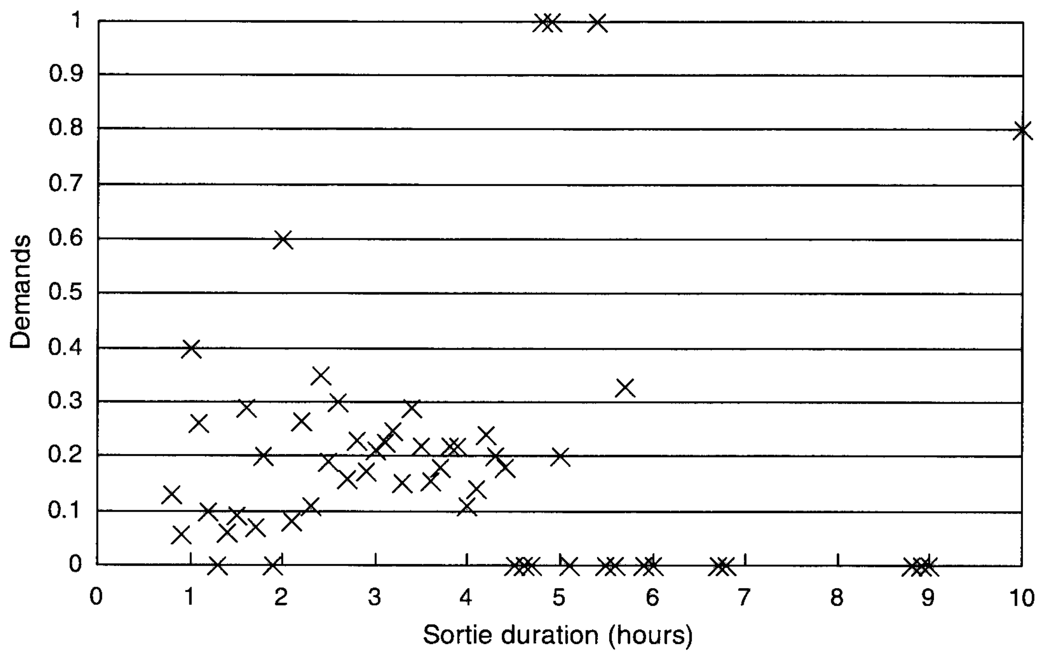

Figure 4-7.
AOR F-16C in 1994; 1,718 A7LA Missions

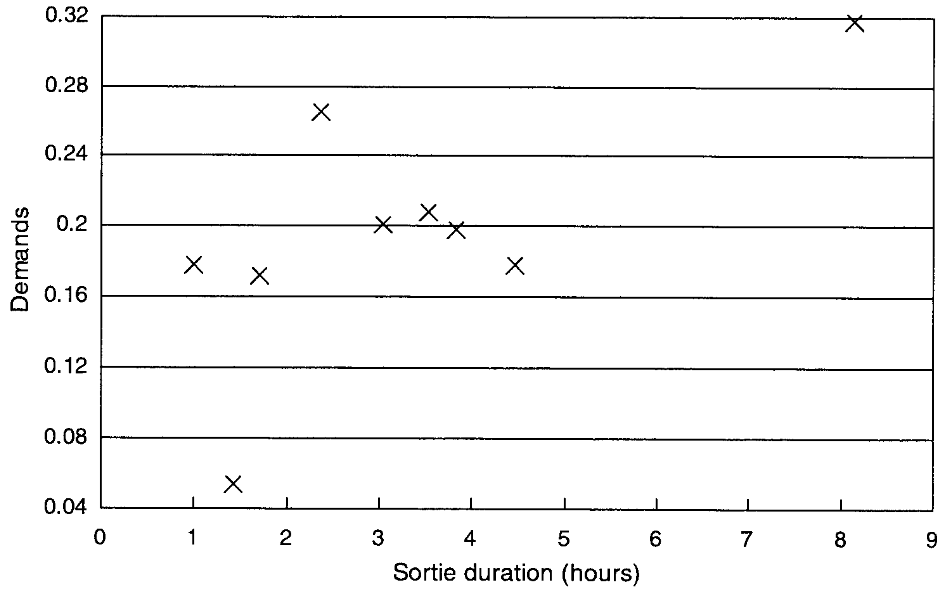

Figure 4-8.
AOR F-16C in 1994; 1,718 A7LA Missions (Aggregated)

The O1PA missions (Provide Comfort) are also longer than the usual peacetime missions; they are similar to the A7LA missions in duration but have a smaller demand rate. After we dropped the 19 sorties of 0.9 hours or less with a high demand rate of 0.20, the remaining 1,101 sorties were analyzed. The slopes are statistically nonsignificant at 9 percent before and 23 percent after adjustment for earlier/last sortie of the day. Although the latter slope is not statistically significant, it is much greater after adjustment because the last sortie of multiple sorties averaged only 2.6 hours, whereas the earlier sorties of multiple sorties averaged 2.94 hours (generally the last sortie of multiple sorties tends to be longer than the earlier sorties).

From the remaining data, we combined similar training missions: T2D, T3D, T3G, T2O, T3O, T20, T30, and T3Q. We then dropped the 4 sorties of 0.1-hour duration with a high demand rate of 0.75 and the 101 longest sorties of 6.7 hours or more with a low demand rate of 0.11. The remaining 72,811 sorties have a slope of 9 percent before adjustment for earlier/last sortie and a 6 percent slope after adjustment; both are statistically significant. These sorties are displayed in Table 4-11.

Table 4-11.
Impact of Sortie Number on Demand (F-16C 1994 Training Missions)

Sortie number of the day	Number of sorties	Average length (hours)	Demands/sortie
Only	20,831	1.44	0.36
1 of multiple	23,122	1.33	0.10
2 of multiple	4,418	1.27	0.09
3 of multiple	1,073	1.24	0.08
4 of multiple	179	1.20	0.11
5 of multiple	10	0.93	0.00
Last	23,178	1.33	0.35
Total/average	72,811	1.35	0.25

However, when the raw data are plotted in Figure 4-9 or the aggregated data in Figure 4-10, the pattern appears rather strange. If we drop the 5,288 sorties of less than 0.9 hours or more than 2.5 hours, the slope is dramatically higher at 24 percent before (15 percent after adjustment for early/last sortie). In an attempt to understand why the results are so sensitive to cropping, we looked at the demand rates by location in Tables 4-12 and 4-13.

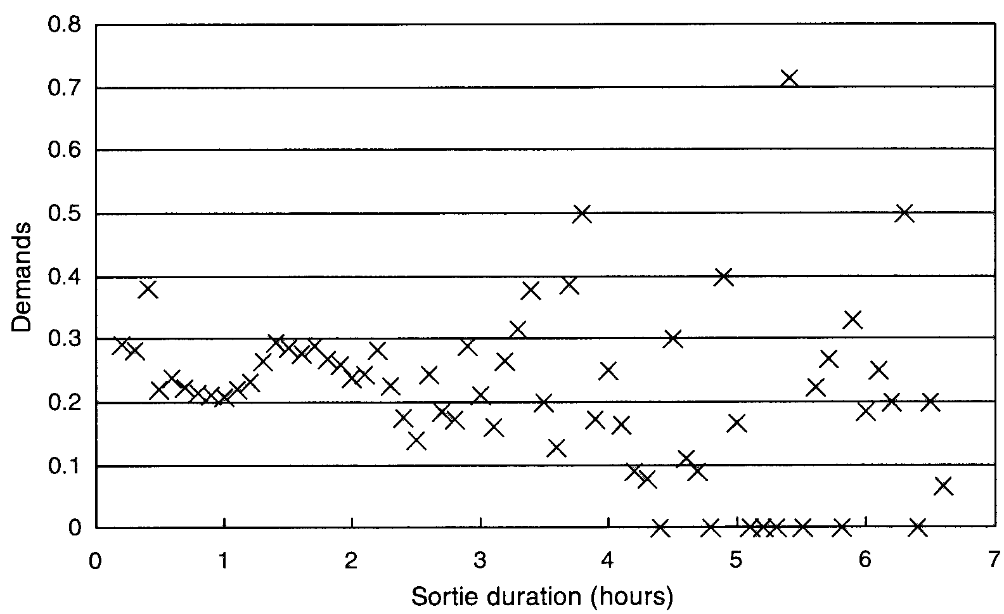

Figure 4-9.
F-16C in 1994; 72,811 Training Missions

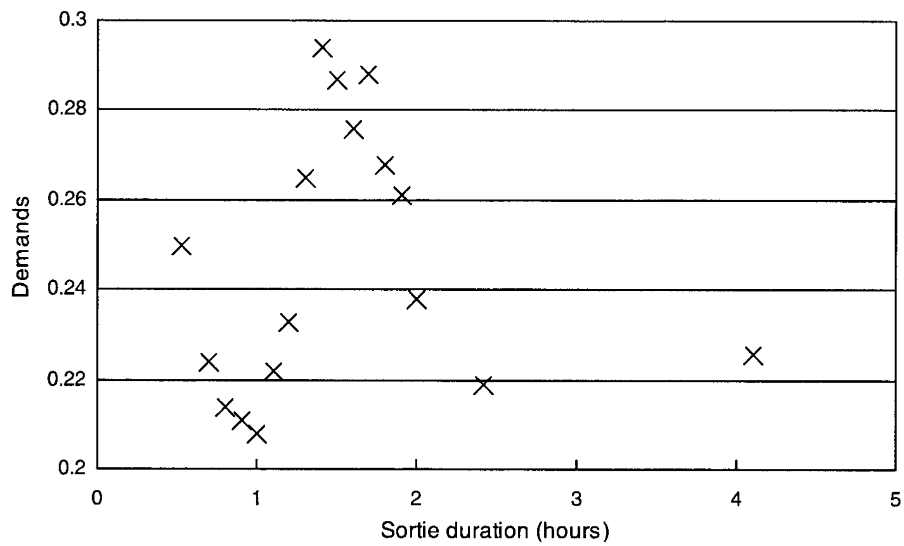

Figure 4-10.
F-16C in 1994; 72,811 Training Missions (Aggregated)

Table 4-12 lists, in decreasing order, the demand rates at regular Air Force bases; Table 4-13 does so for Air National Guard (ANG) and U.S. Air Force Reserve (AFR) bases.[2] Several very small bases were dropped as well as two European bases, which are primarily engaged in support of operational missions over Southwest Asia. We note that only two AFR/ANG bases have higher demand rates than any regular base. Overall, the average number of demands per sortie at the regular bases is almost twice as large, even though the average sortie lengths are almost identical. This seeming anomaly is not surprising to the Air Force personnel we have contacted, because the AFR/ANG pilots — and perhaps more importantly, the maintenance personnel — tend to be more experienced. Another possibility is that the regular Air Force training missions, though coded the same as the AFR/ANG training missions, may put more stress on the aircraft. Although it would be interesting to know the reason for the systematic difference, the important thing is that the two data sets should be analyzed separately.

[2] The analysis results would be essentially unchanged even if a couple of bases were incorrectly identified in the split between regular Air Force and AFR/ANG.

Table 4-12.
F-16C 1994 Sorties and Demand Rates by Location (Regular Air Force Bases)

Location	Total sorties	Average length (hours)	Demands/sortie
Hill, UT	6,876	1.36	0.38
Misawa, Japan	5,567	1.47	0.38
Osan, Korea	1,901	1.29	0.35
Moody, GA	5,575	1.41	0.35
Kunsan, Korea	6,012	1.38	0.34
Nellis, NV	6,073	1.41	0.34
Mountain Home, ID	1,703	1.57	0.26
Luke, AZ	9,030	1.23	0.23
Pope, NC	1,987	1.46	0.22
Shaw, SC	5,952	1.49	0.21
Total/average	50,676	1.39	0.31

Table 4-12 covers about three times as many sorties as does Table 4-13. Thus, when the data in the former are analyzed, the slopes are similar to those above for the full data set. However, the slopes for the group of AFR/ANG bases in Table 4-13 are zero for all training sorties between 0.2 and 6.6 hours, and they are 4 percent before and 3 percent after adjustment for earlier/last sortie on missions between 0.9 and 2.5 hours.

Table 4-13.
F-16C 1994 Sorties and Demand Rates by Location (AFR/ANG Bases)

Location	Total sorties	Average length (hours)	Demands/sortie
New Orleans, LA	1,124	1.33	0.33
Hancock Field, NY	1,219	1.39	0.22
Byrd Field, VA	1,838	1.37	0.20
Eielson, AK	2,765	1.34	0.20
Toledo, OH	1,293	1.29	0.19
Sioux City, IA	1,233	1.30	0.18
Dannelly, AL	1,619	1.36	0.16
Buckley, CO	1,377	1.41	0.16
Springfield, OH	1,548	1.22	0.14
Joe Foss, SD	407	1.73	0.14
Des Moines, IA	1,543	1.53	0.09
Hulman, IN	1,982	1.22	0.07
Total/average	17,948	1.35	0.17

When the slopes for the two groups of data are averaged, weighted by the number of sorties, the slopes are reduced. For all training sorties between 0.2 and 6.6 hours, the slopes are 7 percent before and 4 percent after adjustment for earlier/last sortie; for the 61,499 training sorties between 0.9 and 2.5 hours, the slopes are 21 percent before and 13 percent after adjustment for earlier/last sortie.

We cannot fully account for the large difference in slopes that emerged when the sorties between 0.2 and 0.8 hours and over 2.5 hours are dropped, although it is lessened somewhat by analyzing the data in the two groups above. Since we are anxious not to understate the slopes, we will use the larger slopes of 21 percent and 13 percent from the cropped data in our summaries below.

F-16C/D Worldwide in 1995

There were 60,166 training sorties between 0.9 and 2.5 hours on the F-16C worldwide in our REMIS database for 1995. The data were split as above because the demands per sortie for the USAF bases were 0.27, compared to 0.22 for the AFR/ANG bases. The sortie lengths were almost identical at 1.35 and 1.36, respectively. The slope for the 32,747 regular Air Force sorties was 17 percent before adjusting for last sortie and 9 percent after; the slope for the 27,419 AFR/ANG sorties was 4 percent before and 2 percent after. Overall, the slopes were 11 percent before adjusting for last sortie and 6 percent after.

There were 12,349 training sorties between 0.9 and 2.5 hours for the F-16D worldwide in 1995 as well. The average demands per sortie was 0.28 and the slopes were 7 percent before adjusting for last sortie and 0 after.

F-15A Worldwide

There were 15,134 F-15A sorties worldwide in our REMIS database, which covered the last 8 months of 1993. Again, the variable with the greatest statistical significance is sortie number, as shown in Table 4-14.

We found large differences in demand rate by location. For this reason we have broken out the sorties by mission type as well as by location in Table 4-15. There were 79 distinct mission codes in the data set, which we aggregated into the three groups shown: 999 operational missions beginning with an "O" (these include functional test flights), 331 cross-country training flights with "T3X" codes, 13,804 other training flights. The three groups were selected because of other analyses performed previously. They separate the average demands per sortie into the three rather different rates of 0.48, 0.24, and 0.34, respectively.

Table 4-14.
Impact of Sortie Number on Demand (F-15A Worldwide)

Sortie number of the day	Number of sorties	Average length (hours)	Demands/sortie
Only	4,962	1.39	0.50
1 of multiple	4,836	1.23	0.16
2 of multiple	441	1.14	0.13
3 of multiple	52	1.18	0.17
4 of multiple	7	1.49	0.00
Last of multiple	4,836	1.23	0.39
Total/average	15,134	1.28	0.34

One interesting comparison is between Eglin and Edwards — bases where almost all missions were operational. The number of sorties was small, but the demand rate at Eglin was 60 percent higher. We hypothesized that the Gulf Coast bases, which have the highest demand rates, may be affected by humidity. If humidity can cause failures, we would expect the impact to be greater on electrical systems. By aggregating the demand for all WUCs that are primarily electrical (e.g., electrical system, instruments, communications/navigation gear, fire control, electronic countermeasures), we have almost 60 percent of the demands. When the last column of Table 4-15 is computed by location for this electrical subgroup, the demand rates are almost exactly 60 percent of the total demand rates shown. Thus the humidity hypothesis does not seem to hold water.

Table 4-15.
Sorties and Demand Rates by Mission Type and Location (F-15A Worldwide)

Location	O missions	T3X missions	Other training	Total sorties	Demands/ sortie
Eglin, FL	616	0	0	616	0.52
Tyndall, FL	24	108	1,984	2,126	0.46
New Orleans, LA	14	164	1,976	2,154	0.39
St. Louis, MO	10	0	1,495	1,505	0.36
Portland, OR	51	0	1,932	1,983	0.35
Edwards, CA	172	0	6	178	0.32
Hickam, HI	35	0	1,863	1,898	0.30
Dobbins, GA	24	0	1,829	1,853	0.28
New Amsterdam, Europe	5	59	975	1,039	0.25
Otis, MA	48	0	1,734	1,782	0.23
Total/average	999	331	13,794	15,134	0.34
Demands/sortie	0.48	0.24	0.34	0.34	–

Although the T3X cross-country missions had the smallest maintenance requirement, they were the longest, with an average duration of 2.4 hours. The remaining 14,803 sorties average only 1.25 hours, and about two-thirds of them are within 0.6 hours of the average. This limited dispersion of sortie lengths within each group creates a major problem with the F-15A data. For that reason, we did not analyze the impact of sortie duration on demand for WUC subgroups.

When we analyze the sorties in the "other training" column of Table 4-15, either for each location with 1,700 or more sorties or for all locations combined, we find no relationship between demand and sortie length. Even if we discard the 327 sorties with durations of 0.7 hours or less (with a high demand rate of 0.44) and the 190 sorties with durations of 3 hours or more (with a low demand rate of 0.22), the slope of the regression line is negative, both before and after adjusting for earlier/last sortie of the day. In other words, we cannot find any significant positive relationship between sortie duration and demand.

F-15E Worldwide

This is an analysis of the worldwide REMIS data for the F-15E from about May 1993 through the end of that year. The most significant variable in its impact on demand rate is earlier versus last of multiple sorties in a day, as seen in Table 4-16.

Table 4-16.
Impact of Sortie Number on Demand (F-15E Worldwide)

Sortie number of the day	Number of sorties	Average length (hours)	Demands/sortie
Only	7,486	1.92	0.58
1 of multiple	6,033	1.72	0.19
2 of multiple	489	1.54	0.17
3 of multiple	126	1.40	0.21
4 of multiple	27	1.29	0.00
5 of multiple	1	1.30	0.00
Last of multiple	6,033	1.71	0.55
Total/average	20,195	1.78	0.44

The demand rates are quite similar from one location to another, as shown in Table 4-17. The highest rate — at Eglin — is for only 152 sorties, but the lowest rate — at Lakenheath, England — is for a large number of sorties. Note that

some of the lowest demand rates were at locations with long average sortie durations. Because there are 62 different mission types, our first regression analyses were for certain homogeneous subgroups:

- 5,445 T3GA missions from Seymour Johnson AFB
- 3,447 T3TA missions from Lakenheath, England
- 2,639 T2OT missions from Luke AFB
- 8,091 T3GA missions worldwide.

Table 4-17.
Sorties and Demand Rates by Location (F-15E Worldwide)

Location	Total sorties	Average length (hours)	Demands/sortie
Eglin, FL	152	1.82	0.74
Nellis, NV	1,073	1.54	0.54
Mountain Home, ID	1,178	1.81	0.49
Luke, AZ	3,888	1.59	0.46
Seymour Johnson, NC	7,588	1.77	0.46
Elmendorf, AK	1,936	1.89	0.43
Edwards, CA	188	1.67	0.41
Lakenheath, England	4,192	2.00	0.35
Total/average	20,195	1.78	0.44

The slopes in each case were negative except for the T3TAs at Lakenheath, in which case the slope was not significant. Finally, we performed an analysis for the group of training missions worldwide (T2D, T3D, T3G, T2O, T3O, T20, T30, and T3Q). We dropped the 60 sorties of 0.7 hours or less, which had a large demand rate of 0.58, and the 14 sorties of 8.8 hours or longer, which had a small demand rate of 0.36. The 11,942 remaining sorties do not show a positive slope, either before or after the adjustment for earlier/last sortie of the day.

F-111E Worldwide

This is an analysis of the worldwide REMIS F-111E data from May through November 1993. There were 2,597 sorties from three locations. The demands per sortie after the second of multiple sorties has an extremely large value, unlike anything seen in the other data sets. However, there are only 6 sorties in that group. (See Table 4-18.)

Table 4-18.
Impact of Sortie Number on Demand (F-111E Worldwide)

Sortie number of the day	Number of Sorties	Average length (hours)	Demands/sortie
Only	1,700	2.65	1.05
1 of multiple	445	2.40	0.26
2 of multiple	6	2.00	2.33
Last of multiple	445	2.18	0.94
Total/average	2,596	2.52	0.90

The 1,167 T3TA training missions at Upper Heyford comprise almost half of the total sorties. When these are analyzed as a group, there is a statistically significant slope of 19 percent. When we consider all 2,194 training missions (T2D, T3D, T3G, T2O, T3O, T20, T30, T3Q, and T3T), dropping only the 13 sorties of 0.8 hours or less, which had a large demand rate of 1.62, and the 5 sorties of 5 hours or more, which had a 0 demand rate, we obtained statistically significant slopes of 27 percent before and 33 percent after adjustment for earlier/last sortie of the day.

F-111F Worldwide

This is an analysis of the worldwide F-111F REMIS data from about May 1993 through the end of that year. Three-quarters of the 4,805 sorties were T3GA missions from Cannon AFB, NM; they are displayed in Table 4-19. Demands after the only/last sortie were about three times the rate for earlier sorties of the day.

Table 4-19.
Impact of Sortie Number on Demand (F-111F Cannon AFB T3GA)

Sortie number of the day	Number of sorties	Average length (hours)	Demands/sortie
Only	2,195	2.25	1.29
1 of multiple	614	2.14	0.43
2 of multiple	35	2.04	0.43
Last of multiple	607	2.11	1.09
Total/average	3,451	2.21	1.09

The slope of demand rate as a function of sortie length is negative, and it remains negative after dropping the 34 sorties of 0.6 hours or less (which had a high demand rate of 1.24) and the 16 sorties of 5.7 hours or more (which had a low rate of 0.24). The slope remains negative and nonsignificant even after taking into account earlier/last sortie of the day.

F-117A Worldwide

This is an analysis of the worldwide REMIS data for the F-117A from about May 1993 through October 1994. Since almost all sorties were flown from Holloman AFB, NM, we dropped the small number flown elsewhere. Table 4-20 shows those training missions that lasted between 0.9 and 2.5 hours. Again we found that the demands after the only sortie of the day were quite high. When multiple sorties are flown during a day, the demands tend to decline with each succeeding sortie except the last, when the rate rises again. In this case, the last-sortie demand rate was even higher than that for the only sortie of the day.

Table 4-20.
Impact of Sortie Number on Demand (F-117A Holloman AFB)

Sortie number of the day	Number of sorties	Average length (hours)	Demands/sortie
Only	4,899	1.68	0.44
1 of multiple	1,959	1.61	0.12
2 of multiple	87	1.70	0.13
3 of multiple	2	1.30	0.00
Last of multiple	1,847	1.65	0.50
Total/average	8,794	1.66	0.38

The slopes both before and after adjustment for earlier/last sortie are negative. It is interesting to note that our first data set for the F-117A, comprising about half of the sorties and ending 15 March 1994, resulted in statistically significant slopes of 23 percent before adjustment for earlier/last sortie of the day and 17 percent after. Because these slopes were so large and the F-117A is an important aircraft, we obtained more REMIS data, which produced more typical slopes.

CHAPTER 5

Analysis of REMIS Data — Attack Aircraft

The REMIS A-10/OA-10 worldwide data are for the period of January through August 1994. There were 45,428 sorties in our original data set. We analyzed the group of 36,926 training missions (T2D, T3D, T3G, T2O, T3O, T20, T30, and T3Q) shown in Table 5-1. Before the statistical analysis, we dropped the 4 sorties of 0.1-hour length, which had no demand, and the 79 sorties longer than 6 hours, which had a demand rate of 0.25. The slope of demand rate as a function of sortie length is 31 percent before adjustment for earlier/last sortie of the day and 29 percent after, and both are statistically significant. When we analyzed just the 33,090 training missions between 0.9 and 2.5 hours, the slopes increased dramatically, to 61 percent and 51 percent, respectively.

Table 5-1.
Impact of Sortie Number on Demand (A-10/OA-10 Worldwide)

Sortie number of the day	Number of sorties	Average length (hours)	Demands/sortie
Only	8,180	1.83	0.37
1 of multiple	13,013	1.78	0.07
2 of multiple	1,981	1.40	0.05
3 of multiple	649	1.42	0.05
4 of multiple	177	1.54	0.07
Last of multiple	12,926	1.71	0.33
Total/average	36,926	1.74	0.23

These results are disconcerting, for two reasons: the slopes are much larger than those for the other aircraft analyzed in the preceding chapter, and the slopes are dramatically affected by the cropping procedure for disposing of short and long sorties. In an attempt to understand what is really happening, we show in Table 5-2 a breakout by location of the last set of data for sorties between 0.9 and 2.5 hours, starting with the highest demand rate.

Table 5-2.
Sorties and Demand Rates by Location (A-10/OA-10 Worldwide)

Location	Total sorties	Average length (hours)	Demands/ sortie	Fire control and weapon demands /sortie	Fire control and weapons % of demand
Nellis, NV	865	1.76	0.42	0.14	34.2
Osan, Korea	1,345	1.83	0.33	0.06	19.2
Eielson, AK	1,305	1.99	0.31	0.08	25.8
Davis Monthan, NM	8,590	1.94	0.30	0.08	27.3
McChord, WA	2,526	1.86	0.28	0.07	26.6
Shaw, SC	3,102	1.66	0.27	0.06	20.6
Pope, NC	2,957	1.70	0.22	0.04	20.4
Whiteman, MO	531	1.36	0.22	0.03	13.6
Richards Gebaur, MO	1,202	1.54	0.15	0.04	22.5
Barksdale, LA	1,634	1.41	0.15	0.03	29.2
Martin, MD	1,820	1.60	0.12	0.03	20.2
Bradley, CT	1,723	1.55	0.11	0.02	17.6
Grissom, IN	1,195	1.57	0.10	0.03	29.0
Willow Grove, PA	1,481	1.59	0.10	0.01	7.0
Barnes ANG, MA	893	1.60	0.10	0.01	11.5
Kellogg, MI	1,614	1.67	0.08	0.01	13.6
Spangdahlem, Germany	307	1.86	0.06	0.03	50.0
Total/average	33,090	1.74	0.22	0.05	23.8

Note the tremendous variation in demand rates by location. The bases with high demand are major operating sites, many with gunnery ranges. The bases with smaller demand tend to have fewer sorties and are often ANG sites in urban areas. Since we suspect that there may be more opportunity at the first set of bases for gunnery practice, we show in the last two columns of Table 5-2 the demand rate for the fire control and weapons WUCs and the percentage of total demand represented by these WUCs. This seems to help explain why the demand rates are so different.

Since the bases are so heterogeneous, we divided the data into two groups. The first group of seven bases with the highest demand rates (from Nellis to Pope) plus Spangdahlem have A10 squadrons operated by the USAF and its overseas commands. For this group of 20,997 sorties the slopes were 10 percent before earlier/last sortie adjustment and 3 percent afterwards. The second group of bases have A10 squadrons operated by the AFR/ANG. The slopes for the 12,093 sorties of the second group were 13 percent before earlier/last sortie adjustment and 11 percent afterwards. Averaging over the two groups, weighted by the number of sorties, yields slopes of 11 percent and 6 percent respectively, with only the first one statistically significant.

How did the grouping result in such a dramatic reduction, from slopes of 61 percent and 51 percent to slopes of 11 percent and 6 percent? The answer is that the high-demand USAF bases had sortie durations that averaged about 0.3 hours longer, presumably because the missions being flown were somewhat different, perhaps because of weapons practice. The average demand rate for the USAF bases was 0.29, about 2.4 times as large as the AFR/ANG rate of 0.12; however, the corresponding rates for fire control and weapons were 0.07 and 0.02, and even larger ratio of 3.4. In cases such as this one, where there are such large differences between locations, it is important that bases with similar characteristics be analyzed together.

This effect is a more extreme example of what we observed for the F-16C, where separate analyses of all regular Air Force bases and all AFR/ANG bases gave more credible results than a combined analysis.

CHAPTER 6

Analysis of REMIS Data — Bomber Aircraft

B-1 WORLDWIDE

The REMIS B-1 worldwide data are for the period of October 1993 through October 1994. There were 8,263 sorties in our original data set, which were reduced to the 8,184 training missions shown in Table 6-1. Again we see much higher demand rates on the only or last sortie of the day.

Table 6-1.
Impact of Sortie Number on Demand (B-1 Worldwide)

Sortie number of the day	Number of sorties	Average length (hours)	Demands/sortie
Only	4,040	5.23	1.55
1 of multiple	1,925	4.63	0.34
2 of multiple	254	1.46	0.24
3 of multiple	24	1.95	0.13
4 of multiple	4	0.33	0.00
5 of multiple	2	0.02	0.00
6 of multiple	2	0.20	0.00
7 of multiple	2	0.20	0.00
8 of multiple	2	0.20	0.00
9 of multiple	2	0.25	0.00
10 of multiple	1	0.20	0.00
11 of multiple	1	0.20	0.00
Last of multiple	1,925	2.94	1.83
Total/average	8,184	4.41	1.28

We excluded the 288 sorties less than 0.7 hours in duration and the 142 sorties of longer than 10 hours in duration. For the remaining 7,754 sorties, the slope of demand rate as a function of sortie length is 2 percent before adjustment for earlier/last sortie of the day and 8 percent after, and both are statistically significant. Note that in this case, the slope is larger after the earlier/last sortie adjustment, because the average sortie length is shorter for the last sortie than the overall average.

B-52H Worldwide

The REMIS B-52H worldwide data are for the period of April 1994 through February 1995. There were 3,768 sorties in our original data set. When we analyzed the group of 3,691 training missions (T3) by location, we found that the demand rate at one base (Ellsworth, ND) was less than a third of that at any other base. We discarded these sorties because of our earlier studies with heterogeneous data on the A-10/OA-10, but fortunately this meant losing only 295 sorties. A second base, Fairchild, with only 21 sorties was dropped because it was even more atypical with an average sortie length of 1.88 hours and a demand rate of 0.14. The sorties at the four main operating bases are shown in Table 6-2.

Table 6-2.
Impact of Sortie Number on Demand (B-52H Worldwide)

Sortie number of the day	Number of sorties	Average length (hours)	Demands/sortie
Only	2,694	6.55	1.88
1 of multiple	335	5.30	0.45
2 of multiple	24	2.45	0.00
Last of multiple	322	2.55	1.64
Total/average	3,375	6.02	1.70

We had a discussion with operations personnel, who suggested that we might want to exclude sorties of less than 4 hours, because it would be hard to accomplish a mission in less time. However, as we reviewed the data, it became obvious that dropping those sorties would produce some strange results, since the average duration for the second or last of multiple sorties was only 2.5 hours. Also, this would mean losing 795 sorties, or almost a quarter of the total.

After examining the data, we dropped the 30 sorties of less than an hour, with a high demand rate of 1.90, and the 148 sorties of greater than 10 hours, with a demand rate of 1.82. For the remaining 3,197 sorties the slope of demand as a function of sortie length is 14 percent before adjustment for earlier/last sortie of the day and 21 percent after, and both are statistically significant. Again we note that the latter value is larger because the last sortie of the day tends to be shorter than average. It is interesting to note that these slopes are similar to the 20 percent slope obtained for the B-52D in the 1970 Boeing study shown in Table 1-1.

CHAPTER 7

Analysis of REMIS Data — Reconnaissance Aircraft

E-3 WORLDWIDE

The data are for the first 6 months of 1994. After eliminating sorties of less than an hour duration, there were 2,438 training sorties remaining. The slope was 11 percent, both before and after adjustment for last sortie. Although the last sortie of the day was much shorter than the only sortie of the day, Table 7-1 shows that there were very few multiple sorties.

Table 7-1.
Impact of Sortie Number on Demand (E-3 Worldwide)

Sortie number of the day	Number of sorties	Average length (hours)	Demands/sortie
Only	2,162	6.93	1.96
1 of multiple	144	4.52	0.15
2 of multiple	5	3.14	0
Last of multiple	127	3.60	2.17
Total/average	2,438	6.57	1.86

CHAPTER 8

Analysis of REMIS Data — Transports/ Tankers/SOF Aircraft

C-130H WORLDWIDE

The REMIS worldwide data for the C-130H are for the period of October 1993 to October 1994. There were 29,801 sorties in our original data set. We analyzed a group of 27,919 sorties, excluding the 1,770 sorties shorter than 0.5 hours (with a low demand rate of 0.14) and the 112 sorties longer than 9 hours (with a high demand rate of 0.54). The slope of demand as a function of sortie duration is 15 percent and statistically significant before adjustment for earlier/last sortie of the day; it is 6 percent after.

The data for the reduced set of sorties are shown in Table 8-1. Again we see much higher demand rates after the only/last sortie of the day. The sortie durations in this data set are particularly short, and there was one aircraft with 15 sorties in a single day.

AC-130, EC-130, HC-130, AND MC-130 WORLDWIDE

This data set contains 50,452 sorties from January 1994 through August 1996, on a variety of related aircraft, as shown in Table 8-2. To increase comparability, we have displayed only the training sorties (coded "T") from 1 to 6 hours.

The AC-130A/H/U Spectre aircraft are gunships with a tremendous variation in age from the A model of the mid-1950s to the U model of the late 1980s. The dramatically different demand rates and sortie lengths indicate that it would be unwise to aggregate the data for these three aircraft types. In particular, the low demand rates for the AC-130A almost surely result from the fact that this series was scheduled to retire during 1995 (the last sorties were during September 1995).

Table 8-1.
Impact of Sortie Number on Demand (C-130H Worldwide)

Sortie number of the day	Number of sorties	Average length (hours)	Demands/sortie
Only	5,401	3.22	0.36
1 of multiple	8,059	2.03	0.05
2 of multiple	3,684	1.50	0.04
3 of multiple	1,622	1.24	0.04
4 of multiple	637	1.14	0.02
5 of multiple	259	1.02	0.01
6 of multiple	89	0.92	0.00
7 of multiple	35	0.94	0.03
8 of multiple	16	0.79	0.00
9 of multiple	6	0.95	0.00
10 of multiple	3	0.77	0.00
11 of multiple	3	0.70	0.00
12 of multiple	2	0.75	0.00
13 of multiple	2	0.80	0.00
14 of multiple	1	0.50	0.00
Last of multiple	8,100	2.02	0.39
Total/average	27,919	2.11	0.21

Table 8-2.
Types of Aircraft

Aircraft MDS	Number of aircraft	Number of T sorties 1-6 hrs.	Years built	Average length (hours)	Demands/ sortie
AC-130A	9	1,050	1953 – 1956	2.50	0.89
AC-130H	8	872	1969	3.55	2.25
AC-130U	8	549	1987 – 1990	3.69	1.47
EC-130E ABCCC	9	638	1962 – 1963	3.55	0.84
EC-130E Psy. War.	6	1,289	1963	2.83	0.38
EC-130H	15	1,299	1964 – 1973	4.25	1.31
HC-130N USAF	12	1,261	1969	3.06	0.83
HC-130N AFR	3	379	1969	2.34	0.48
HC-130N ANG	3	458	1988 – 1990	2.22	0.31
HC-130P USAF	26	3,715	1964 – 1966	3.10	0.75
HC-130P AFR	5	785	1964 – 1966	2.50	0.44
HC-130P ANG	7	973	1964 – 1966	2.46	0.34
MC-130E	14	1,716	1962 – 1964	3.05	1.35
MC-130H	24	4,944	1983 – 1990	2.90	0.69

The EC-130E include two groups: nine aircraft used as Airborne Battlefield Command and Control Centers and six used for psychological warfare operations and operated by the ANG. The ANG units have slightly shorter sorties and demand rates that are only 40 percent as large. Thus, aggregating these two groups for analysis would give an erroneous large positive slope for the relationship of demand to sortie length.

The HC-130N/P are Combat Shadow aircraft dedicated to Special Operations Forces (SOF) missions. Their primary mission is to conduct refueling of special operations helicopters in a no- to low-threat environment. Again we have separated the data for the regular Air Force from the AFR and ANG because the latter tend to have slightly shorter missions and much lower demand rates. In the case of the HC-130N, we separated the AFR from ANG because the latter aircraft are 20 years newer with much lower demand rates.

The MC-130E/H are Combat Talon aircraft equipped for use in night/adverse-weather, low-level, deep-penetration tactical missions. They are equipped for in-flight refueling with modified cargo ramps for high-speed aerial delivery. There were several other aircraft, such as the HC-130H, LC-130H, NC-130, and WC-130H, for which the number of sorties was inadequate to perform any analyses.

We limited our analyses to training missions, coded "T" because these are the majority of missions (excluding operational missions coded "A" or "O"). These were further restricted to the range of 1 to 6-hour sortie durations. An initial analysis on all 9,391 sorties from Eglin resulted in a slope of 12 percent before adjustment for the last sortie effect and 11 percent after adjustment. However, as seen in Table 8-2, there are such large differences in demand rates by aircraft type and by user (regular Air Force versus AFR/ANG) that an analysis of such aggregated data is not credible.

Thus, we analyzed each group in Table 8-2 with at least 1,000 sorties, resulting in the cases shown in Table 8-3.[1] Some have speculated that the AFR/ANG demand rates are lower than those for the regular Air Force because the pilots and maintenance personnel are more experienced. Or it may be that the missions are really somewhat different, though coded the same, with the regular Air Force missions including more time on the firing ranges. While it would be interesting to know why these same differences are observed on several aircraft types, the important thing is to analyze the data sets separately.

For example, the demand rates and sortie durations in Table 8-2 for the HC-130P become larger as one moves from the ANG to the AFR and the regular Air Force. If these sorties are aggregated for analysis, the slope is artificially inflated. When each of the three using groups is analyzed separately and the results averaged, we obtain the results shown in Table 8-3.

[1] Although there are slightly more than 1,000 sorties for the AC-130A, it was not analyzed because it was retired in 1995.

Table 8-3.
Slope by Aircraft Type

Aircraft type	Total sorties	Slope before adjustment for last sortie (%)	Slope after adjustment for last sortie
EC-130E	1,927	12	6
EC-130H	1,299	3	6
HC-130P	5,473	35*	20*
MC-130E	1,716	42*	26*
MC-130H	4,944	37*	21*

* Statistically significant at 95 percent level.

KC-135 WORLDWIDE

The worldwide REMIS KC-135 data are for the period April 1994 to March 1995. After eliminating duplicate records, there were 24,200 sorties. We analyzed the group of 17,504 T3 training sorties with durations between 0.5 and 10 hours. The slope of demand rate as a function of sortie length is 10 percent before adjustment for earlier/last sortie of the day and 12 percent after, and both are statistically significant.

The data for the reduced set of sorties are shown in Table 8-4. Again we see much higher demand rates after the only/last sortie of the day.

Table 8-4.
Impact of Sortie Number on Demand (KC-135 Worldwide)

Sortie number of the day	Number of sorties	Average length (hours)	Demands/sortie
Only	9,662	3.91	0.64
1 of multiple	3,619	3.13	0.14
2 of multiple	529	1.72	0.10
3 of multiple	46	1.50	0.09
4 of multiple	5	1.18	0.00
Last of multiple	3,643	2.51	0.79
Total/average	17,504	3.39	0.55

C-141 WORLDWIDE

The data for the C-141 and C-5 come from the Air Mobility Command G081 system, and they differ somewhat from the REMIS data used elsewhere. In both cases, the data included landing location as well as takeoff location. Using

landing location, we found that the demand rate was much higher when the sortie ended at a home station. This appears to be another instance of deferred maintenance, although the differences in the demand rates are much larger than those observed in any other data sets.

The data cover the first 6 months of 1994 and (dropping the very short and long sorties) there are 12,501 sorties between 0.6 and 7 hours. In this case, the demands per sortie were 3.81 and the sortie length averaged 2.94 hours for the 3,412 missions flown to a home station; in the other 9,089 sorties, the demands per sortie were only 0.71 and the average sortie length was only 2.68 hours.

In the case of transports flying around the world, the last sortie of the day is less meaningful. Instead we used the dummy variable to measure the home station impact. The slope before accounting for home station was 5 percent, and 1 percent after.

C-5 Worldwide

The data are for the first 6 months of 1994. We retained the 2,825 sorties between 1 and 9 hours for analysis. Here the demands per sortie for sorties ending at a home station were 20 times as large as for sorties landing elsewhere, because of the complexity of the C-5. The 810 home-base sorties had 5.06 demands per sortie as contrasted with the 2,015 other sorties with 0.24 demands per sortie. The average sortie lengths were 4.03 and 4.00, respectively.

A plot of the two groups of data suggested different slopes. Thus, instead of using a dummy variable, we analyzed each group separately and then averaged the slopes, obtaining 5 percent.

CHAPTER 9

Analysis of REMIS Data — Helicopters

INTRODUCTION

We obtained REMIS data on five types of helicopters for the period from August 1995 through July 1996. Unfortunately, not enough data were available to analyze the HH-1H Iroquois, a general-purpose helicopter that entered the inventory in 1970.

UH-1N IROQUOIS

This is a twin-engine version of the UH-1 utility helicopter built in 1968 and 1969 and used for missile-site support duties and administrative airlift. We had data on 11,099 sorties, of which 5,841 were training sorties having an average demand rate of 0.05 and an average sortie duration of 1.42 hours. We dropped the shortest missions, with durations of 0.3 hours or less, and the longest missions, with durations of more than 2.8 hours, which had a lower demand rate of 0.02. The remaining 5,318 training sorties had statistically significant slopes of 22 percent before and 7 percent after adjusting for earlier/last sortie of the day.

There were a large number of operational missions (coded "A" and "O") in this data set as well. The original 5,168 such missions had a demand rate of 0.04 with a shorter average sortie duration of only 0.71 hours. After dropping the shortest sorties, of 0.1 hours, and the longest sorties, of more than 1.5 hours, there were 4,461 sorties for analysis. The slopes before and after adjustment for earlier/last sortie were 60 percent and 10 percent, respectively. Over the total of 9,779 training sorties, the average slopes were 39 percent and 8 percent, respectively.

HH-60G PAVE HAWK

These are modified Black Hawks used for combat search and rescue and various mission support activities worldwide. They entered the inventory between 1981 and 1992. Our data consist of 13,472 sorties, of which 10,189 were training sorties having an average demand rate of 0.21 and an average sortie duration of 1.9 hours. We dropped the shortest missions, with durations of 0.5 hours or less, and the longest missions, with durations of more than 3.5 hours. The remaining 8,426 training sorties had a slope of 27 percent before and 15 percent after adjusting for earlier/last sortie of the day.

MH-53J Pave Low

These aircraft entered the inventory between 1966 and 1973 and were modified by Sikorsky in 1986 to a sophisticated configuration, including terrain-following and terrain-avoidance radar, Global Positioning System, Inertial Navigational System, Doppler, secure communications, missile jammers, chaff dispensers, radar warning receivers, and plume detectors. There were 2,694 sorties, of which the 1,515 training sorties were selected for analysis. We dropped the 100 shortest training missions, with durations of 0.4 hours or less, and the 23 longest missions, with durations of more than 6 hours. The remaining 1,392 sorties had an average demand per sortie of 0.74 and an average sortie duration of 2.69 hours.

The slope before adjustment for earlier/last sortie was 44 percent and after adjustment was 23 percent, and both were statistically significant.

MH-60G Pave Hawk

These modified Black Hawks are used for infiltration/exfiltration and personnel recovery in SOF activities. After retaining the "T" training missions between 0.5 and 4 hours, there were only 929 sorties. Although this is slightly below the 1,000-sortie threshold for analysis that we have used elsewhere, the results are included because this helicopter is important. The slopes were statistically significant at 68 percent before and 15 percent after adjustment for earlier/last sortie. This is an interesting case, because it has the highest pre-adjustment slope (the only aircraft over 50 percent). Furthermore, the effect of the earlier/last sortie adjustment is greater than that for any other aircraft. For this reason, we display the detailed data by sortie in Table 9-1.

The demand rates after only/last sortie of the day are 20 to 25 times as large as after earlier of multiple sorties. This is a far larger effect than we have seen for any other aircraft (usually there is a factor of 4 or 5). Of course, there are very few sorties.

The other problem with so few sorties is that the slope is more likely to be affected by our cropping strategy. In particular, we dropped the 162 training missions of less than 0.5 hours, which had a very low demand rate of 0.15, and 142 missions of more than 4 hours, with a large demand rate of 0.979. When the regressions are rerun with all 1,233 training sorties, the slopes before and after adjustment for earlier/last sortie drop to 45 percent and 14 percent, respectively. It is a little surprising that the unadjusted slope drops so much, and it tends to throw suspicion on the original value of 68 percent. In contrast, the slopes after adjustment, which we believe are more meaningful, are very similar. Even though it is likely that the 68 percent slope is an overstatement, we have retained it in our summary statistics because we want to give large slopes every benefit of the doubt. On the other hand, the similarity of the MH-60G and HH-60G suggest that the slopes for both should be averaged.

Table 9-1.
Impact of Sortie Number on Demand (MH-60G Worldwide)

Sortie number of the day	Number of sorties	Average length (hours)	Demands/sortie
Only	130	2.48	0.80
1 of multiple	255	1.88	0.04
2 of multiple	140	1.58	0.04
3 of multiple	67	1.34	0.02
4 of multiple	32	1.16	0.03
5 of multiple	17	1.15	0.00
6 of multiple	10	0.92	0.00
7 of multiple	5	1.12	0.00
8 of multiple	2	0.65	0.00
Last of multiple	265	2.03	1.05
Total/average	929	1.86	0.43

CHAPTER 10

Summary

This chapter summarizes the data analyses of Chapters 4 through 9. Table 10-1 shows the slope of demand as a function of sortie length obtained by regression for each data set. The first column of numbers is the regression slope, where the independent variable is sortie length and the dependent variable is demands. Thus, 18 percent in the first row indicates that the best estimate is that after the demand generated by a 1-hour sortie, each successive hour of sortie duration is estimated to add 18 percent more demand (on average). The asterisk (*) following a slope indicates that the coefficient is significantly different from zero at the 95 percent level of significance (i.e., in a data set of the indicated size, there is less than a 5 percent chance that the true slope is zero).

The second column of numbers is the slope taking into account the impact of an additional independent variable, earlier sortie versus last sortie of multiple sorties during the day. Thus, the 13 percent in the first row means that when adjusted for sortie number during the day, the estimated impact of sortie length on demand is 13 percent for each additional hour of sortie duration after the first hour. The reason why the numbers in the second column tend to be lower than those in the first is that there is usually a positive correlation between last sortie and sortie length — i.e., the last sortie of the day tends to be longer than average.

Since the data for the F-15C/D and the F-16C/D were broken into several groups and analyzed separately, subtotals for those two aircraft are provided in Table 10-1. Also, totals are provided for each major category of aircraft: tactical fighters, attack, bombers, reconnaissance, transports/ tankers, and helicopters.

Many of the slopes in both columns are zeroes because the slope from regression is negative, even though a negative slope is ruled out by the physics of our problem. (An aircraft with a given number of demands after a certain number of hours in a sortie cannot reduce the number of demands by extending the length of the sortie). The number of sorties in the last column pertains to the number of observations used in each regression, but there were over 700 thousand sorties from which these analyses were extracted. The unanalyzed sorties were for aircraft types or mission codes with fewer than 1,000 sorties.

Table 10-1.
Summary of Slopes (Percentage)

System	Before adjustment for sortie number	After adjustment for sortie number	Number of sorties
F-15C/D Langley	18*	13*	7,020
F-15C/D AOR 1993	9	9	1,178
F-15C/D 1993	0	0	16,522
F-15C/D AOR 1994	0	0	709
F-15C/D 1994	0	0	15,514
F-15C/D 1995	0	0	20,329
F-15C/D total/average	2	2	61,272
F-16C AOR	10	10	1,718
F-16C O1PA	9	23	1,101
F-16C 1994	21*	13*	61,499
F-16C 1995	11*	6*	60,166
F-16D 1995	7	0	12,349
F-16C/D total/average	15*	9*	136,833
F-15A	0	0	13,287
F-15E	0	0	11,942
F-111E	27*	33*	2,176
F-111F	0	0	3,401
F-117A	0	0	8,794
Fighters total/average	10*	6*	237,705
A-10, OA-10 attack	11*	6	30,090
B-1	2*	8*	7,754
B-52H	14*	21*	3,197
Bombers total/average	6*	12*	10,951
E-3 recon	11*	11*	2,438
C-130H	15*	6*	27,919
EC-130E	12	6	1,927
EC-130H	3	6	1,299
HC-130P	35*	20*	5,473
MC-130E	42*	26*	1,716
MC-130H	37*	21*	4,944
KC-135	10*	12*	17,504
C-141	5*	1	12,501
C-5	5	5	2,825
Transports/tankers total/average	15*	9*	76,108
UH-1N	39*	8	9,779
HH-60G	27*	15*	8,426
MH-53J	44*	23*	1,392
MH-60G	68*	15*	929
Helicopters total/average	36*	12*	20,526
Total/average	12*	7*	380,818

*Statistically significant at 95 percent level.

Earlier versus last sortie of the day is more important than sortie length in determining demand. As explained at the end of Chapter 11, we believe that the higher demand rate following the last of multiple sorties in a day is primarily due to deferred maintenance. Thus, the demand after the earlier sorties is understated, while after the last sortie it is overstated. This problem is taken into account in the adjusted slopes of the third column, which we believe are more meaningful. Overall, 24 different aircraft were studied, and 13 of the adjusted slopes are positive and statistically significant.

At the bottom of Table 10-1, we have computed an average slope of 12 percent before adjustment for earlier/last sortie and 7 percent after adjustment. These were obtained by taking each slope, including the nonsignificant slopes, multiplying by the number of sorties, and then dividing the sum of these products by the total of 380,818 sorties. Even these averages are an overstatement of the actual averages, which would have used the negative slopes instead of the zeros shown in Table 10-1.

Remember that we discarded short sorties with large demand rates and long sorties with small demand rates. Some of the short sorties were terminated early for maintenance, and we are interested in the relationship of demand to planned sortie lengths. Long sorties with small demand rates were excluded because some may have been deployments to another site, or the missions themselves may have been different. This procedure increases the regression slopes in Table 10-1, and yet there are still only 13 of 24 that are significant.

A slope of 100 percent would indicate pure flying hours, and a slope of zero percent, pure sorties. Since every adjusted slope is less than 50 percent, number of sorties is a better predictor of demand than flying hours. However, the adjusted slope exceeds 10 percent for 10 aircraft types, including 4 transports and 3 helicopters.

We believe that a 10 percent slope is a reasonable overall planning factor for the impact of sortie duration on demand. However, a slope of 20 percent may be appropriate for bombers, transports/tankers, and helicopters. Also, it is likely that there are some components whose demands have a greater relationship to flying hours than a 10 percent slope. Although the data on any individual item are insufficient to test that hypothesis, it is possible to do some testing at the system level (two-digit WUC). In Chapter 11, we describe some analyses of F-16C data that resulted in larger slopes of 22 percent for fire control systems and 32 percent for electronic warfare systems and similar slopes for the F-15C/D. Since these slopes are still less than 50 percent, it reinforces our conclusion that demand is much more related to sorties than to flying hours.

Two caveats should be noted concerning this conclusion. First, there were only a limited number of long-duration sorties, so that any extrapolation to very long durations may be inaccurate. Second, our data were maintenance data, and there is some difference between demands on supply and maintenance actions.

Chapter 11

Analysis of Other Factors Affecting Demand

Introduction

In this chapter, we use data from Chapters 4 through 10 to investigate phenomena other than the impact of sortie duration on demand. First, we assess how the demand rate varies with the number of days between sorties. Then we examine whether high or low demand rates for specific aircraft tend to persist over time, and whether there is a correlation between demand and utilization. The next several sections describe what was done to find WUCs that may have a greater relationship to flying hours. The final section presents evidence that the higher demand rate following the last of multiple sorties during a day is more likely to result from deferred maintenance than it is from a grounding condition.

Effect of Utilization Rate

Part of our study was devoted to determining the effect of utilization rate on demand. To do so, we compared sorties that followed a period of relative idleness with those that did not. First, to eliminate mission-type effects, we studied demand rates for "T" (training) type missions only. Second, to eliminate variations caused by deferred maintenance, we looked only at demand rates for sorties that were the only sortie of the day. Finally, we looked only at cases where the previous sortie had no failures. (If the aircraft had been worked on since the last sortie, then the number of days until the next sortie might be correlated with how badly the aircraft was broken. This could in turn be correlated with how likely it was to be fixed properly).

The worldwide F-15C/D data from 1993 through 1995 in Chapter 4 were aggregated to increase the sample size. The F-16C data were combined for 1994 and 1995. Table 11-1 shows the number of days since the previous sortie, the number of sorties that qualify under the criteria above, the demand rate, and the break rate. The demand rate is greater than the break rate because a break may be caused by one demand on a sortie or by more than one.

None of the daily increases is statistically significant, and the rates themselves are quite small. It would be interesting to perform other analyses of utilization's influence on demand. For example, do aircraft that fly more hours or more sorties tend to have lower demand rates? We will examine this question in the next section, but first it is important to recognize certain limitations on our

Table 11-1.
Demand and Break Rates as a Function of Utilization

Number of days since previous sortie	F-15C/D			F-16C		
	Number of sorties	Demand rate	Break rate	Number of sorties	Demand rate	Break rate
1	3,787	0.54	0.39	6,657	0.22	0.17
2	1,107	0.54	0.44	1,658	0.20	0.16
3	893	0.64	0.50	1,173	0.29	0.21
4	554	0.65	0.51	945	0.23	0.19
5	369	0.67	0.45	546	0.28	0.23
Daily increase	–	0.04	0.03	–	0.01	0.01

ability to analyze this question with the data at hand. Suppose we find that aircraft with more sorties have lower demand rates? This phenomenon could represent a cause, or it could be an effect (for instance, it would be an effect if aircraft with low demand rates during the day were assigned extra sorties — a practice we believe may be common).

The best way to test whether higher utilization leads to lower demand rates is to conduct a controlled experiment such as the one described in Appendix A. In the absence of a controlled experiment, the group of aircraft should be similar at the start of any comparison period. That is why we chose aircraft that had no demands on their previous sortie as the basis for comparison in the analysis in this section. Unfortunately, we have been unable to think of other analyses that would ensure comparability and ample sample size, particularly in view of the deferred maintenance phenomenon.

Persistence of Demand Rates Over Time

Are there "good" aircraft and "lemons?" That is, do some tail numbers consistently have lower (or higher) demand rates? This is the question we want to address in this section. The data are from 6,293 T30A missions flown by 66 F-15C/D aircraft from Kadena AFB between May 1993 and the end of that year.

We broke this 234-day period into six equal subperiods of 39 days each and computed the demand rate by tail number in each. Eliminating any aircraft that were not present during all the subperiods, there were 4,758 sorties by 39 tail numbers, as shown in Table 11-2. The 39 four-digit tail numbers appear in the first column. Their demands (D1 through D6) and sorties (S1 through S6) are shown for each of the six subperiods. The next six columns (R1 through R6) show the demand rate (number of demands divided by number of sorties) for each tail number in each of the six subperiods. The next five columns show the demand rate during various combinations of subperiods (1 and 2, 3, and 4, 5,

Table 11-2.

Demands, Sorties, and Demand Rates for 39 Kadena-Based F-15C/Ds in 1993

Tail Number	Demands (D) and Sorties ($) for subperiods 1 – 6												Dema	
	D1	S1	D2	S2	D3	S3	D4	S4	D5	S5	D6	S6	R1	R2
61	0	1	11	18	3	4	9	18	8	16	25	39	0.00	0.61
8469	8	18	27	38	15	24	8	11	10	29	4	18	0.44	0.71
8473	0	9	10	22	16	29	14	22	5	6	14	26	0.00	0.45
8474	11	15	15	25	12	22	18	22	7	26	5	6	0.73	0.60
8476	8	5	24	28	24	32	14	28	11	21	17	31	1.60	0.86
8478	8	19	5	17	14	21	13	23	10	20	5	16	0.42	0.29
8479	7	14	5	11	10	23	8	27	17	28	30	22	0.50	0.45
8486	2	6	10	14	26	23	13	25	8	25	18	21	0.33	0.71
8487	4	6	9	28	16	21	12	23	9	19	17	34	0.67	0.32
8489	2	18	12	31	11	17	5	18	2	6	9	19	0.11	0.39
8491	7	8	7	8	9	20	4	32	2	25	13	28	0.88	0.88
8493	13	22	7	10	17	17	8	26	10	29	15	38	0.59	0.70
8494	4	9	8	22	8	28	4	17	6	33	6	21	0.44	0.36
8496	10	11	12	28	8	25	15	27	5	28	6	22	0.91	0.43
8497	8	11	22	31	10	25	6	9	7	12	4	26	0.73	0.71
8498	9	18	18	40	8	9	8	37	3	17	17	25	0.50	0.45
8499	8	13	6	37	9	10	17	29	3	12	12	17	0.62	0.16
8501	9	16	20	29	16	29	9	11	5	24	0	2	0.56	0.69
8502	3	20	5	24	6	8	2	12	9	22	8	32	0.15	0.21
8503	3	1	27	20	2	21	5	18	0	27	1	29	3.00	1.35
8504	4	13	8	20	22	30	18	24	7	22	9	34	0.31	0.40
8508	2	8	13	29	11	23	19	22	5	21	4	3	0.25	0.45
8509	5	23	6	14	9	21	7	10	7	14	7	16	0.22	0.43
8511	2	11	9	38	10	17	20	27	11	24	11	20	0.18	0.24
8515	6	11	17	40	6	26	7	20	1	6	9	18	0.55	0.43
8520	1	4	15	26	10	24	10	19	11	24	22	38	0.25	0.58
8522	6	21	9	20	13	16	33	17	1	4	16	31	0.29	0.45
8528	3	15	18	24	9	20	34	21	7	24	22	40	0.20	0.75
8529	5	27	19	38	4	1	5	3	5	12	12	36	0.19	0.50
8531	8	10	15	21	7	24	7	18	6	16	21	19	0.80	0.71
8536	12	7	9	27	9	25	12	27	8	22	9	14	1.71	0.33
8539	14	6	9	20	7	18	8	36	3	9	15	24	2.33	0.45
8541	3	3	17	12	10	25	8	10	8	15	10	25	1.00	1.42
8543	6	11	20	27	11	31	6	19	5	7	1	4	0.55	0.74
8544	11	17	8	29	3	24	4	8	14	29	10	36	0.65	0.28
8545	2	3	15	27	6	25	18	27	8	15	16	28	0.67	0.56
8547	6	16	9	40	13	18	5	24	4	16	14	38	0.38	0.23
8567	18	10	16	31	6	36	12	19	5	16	10	29	1.80	0.52
8569	4	17	5	6	12	31	10	26	9	18	1	4	0.24	0.83
Average	6.2	12	13	25	11	22	11	21	7	19	11	24	0.66	0.55

* Number of demands divided by number of sorties.

Demand rates* (R) for subperiods 1 – 6						Demand rates for subperiod combinations					Total/average		
R1	R2	R3	R4	R5	R6	R12	R34	R56	R123	R456	D	S	R
.00	0.61	0.75	0.50	0.50	0.64	0.58	0.55	0.60	0.61	0.58	56	96	0.58
44	0.71	0.63	0.73	0.34	0.22	0.63	0.66	0.30	0.63	0.38	72	138	0.52
.00	0.45	0.55	0.64	0.83	0.54	0.32	0.59	0.59	0.43	0.61	59	114	0.52
73	0.60	0.55	0.82	0.27	0.83	0.65	0.68	0.38	0.61	0.56	68	116	0.59
60	0.86	0.75	0.50	0.52	0.55	0.97	0.63	0.54	0.86	0.53	98	145	0.68
42	0.29	0.67	0.57	0.50	0.31	0.36	0.61	0.42	0.47	0.47	55	116	0.47
.50	0.45	0.43	0.30	0.61	1.36	0.48	0.36	0.94	0.46	0.71	77	125	0.62
.33	0.71	1.13	0.52	0.32	0.86	0.60	0.81	0.57	0.88	0.55	77	114	0.68
67	0.32	0.76	0.52	0.47	0.50	0.38	0.64	0.49	0.53	0.50	67	131	0.51
11	0.39	0.65	0.28	0.33	0.47	0.29	0.46	0.44	0.38	0.37	41	109	0.38
88	0.88	0.45	0.13	0.08	0.46	0.88	0.25	0.28	0.64	0.22	42	121	0.35
59	0.70	1.00	0.31	0.34	0.39	0.63	0.58	0.37	0.76	0.35	70	142	0.49
44	0.36	0.29	0.24	0.18	0.29	0.39	0.27	0.22	0.34	0.23	36	130	0.28
91	0.43	0.32	0.56	0.18	0.27	0.56	0.44	0.22	0.47	0.34	56	141	0.40
73	0.71	0.40	0.67	0.58	0.15	0.71	0.47	0.29	0.60	0.36	57	114	0.50
50	0.45	0.89	0.22	0.18	0.68	0.47	0.35	0.48	0.52	0.35	63	146	0.43
62	0.16	0.90	0.59	0.25	0.71	0.28	0.67	0.52	0.38	0.55	55	118	0.47
56	0.69	0.55	0.82	0.21	0.00	0.64	0.63	0.19	0.61	0.38	59	111	0.53
15	0.21	0.75	0.17	0.41	0.25	0.18	0.40	0.31	0.27	0.29	33	118	0.28
.00	1.35	0.10	0.28	0.00	0.03	1.43	0.18	0.02	0.76	0.08	38	116	0.33
31	0.40	0.73	0.75	0.32	0.26	0.36	0.74	0.29	0.54	0.43	68	143	0.48
25	0.45	0.48	0.86	0.24	1.33	0.41	0.67	0.38	0.43	0.61	54	106	0.51
22	0.43	0.43	0.70	0.50	0.44	0.30	0.52	0.47	0.34	0.53	41	98	0.42
18	0.24	0.59	0.74	0.46	0.55	0.22	0.68	0.50	0.32	0.59	63	137	0.46
55	0.43	0.23	0.35	0.17	0.50	0.45	0.28	0.42	0.38	0.39	46	121	0.38
25	0.58	0.42	0.53	0.46	0.58	0.53	0.47	0.53	0.48	0.53	69	135	0.51
29	0.45	0.81	1.94	0.25	0.52	0.37	1.39	0.49	0.49	0.96	78	109	0.72
20	0.75	0.45	1.62	0.29	0.55	0.54	1.05	0.45	0.51	0.74	93	144	0.65
19	0.50	4.00	1.67	0.42	0.33	0.37	2.25	0.35	0.42	0.43	50	117	0.43
80	0.71	0.29	0.39	0.38	1.11	0.74	0.33	0.77	0.55	0.64	64	108	0.59
71	0.33	0.36	0.44	0.36	0.64	0.62	0.40	0.47	0.51	0.46	59	122	0.48
33	0.45	0.39	0.22	0.33	0.63	0.88	0.28	0.55	0.68	0.38	56	113	0.50
00	1.42	0.40	0.80	0.53	0.40	1.33	0.51	0.45	0.75	0.52	56	90	0.62
55	0.74	0.35	0.32	0.71	0.25	0.68	0.34	0.55	0.54	0.40	49	99	0.49
65	0.28	0.13	0.50	0.48	0.28	0.41	0.22	0.37	0.31	0.38	50	143	0.35
67	0.56	0.24	0.67	0.53	0.57	0.57	0.46	0.56	0.42	0.60	65	125	0.52
38	0.23	0.72	0.21	0.25	0.37	0.27	0.43	0.33	0.38	0.29	51	152	0.34
80	0.52	0.17	0.63	0.31	0.34	0.83	0.33	0.33	0.52	0.42	67	141	0.48
.24	0.83	0.39	0.38	0.50	0.25	0.39	0.39	0.45	0.39	0.42	41	102	0.40
.66	0.55	0.62	0.59	0.37	0.50	0.56	0.56	0.43	0.52	0.46	58.9	122	0.48

and 6, 1 through 3, and 4 through 6). Finally, the last three columns (D, S, and R) display, respectively, the total number of demands, the total number of sorties, and the combined demand rate for the entire period. From these data, we performed the following analyses:

- The correlation of demand rates in subperiods 1 and 2 was computed across the 39 aircraft. This procedure was repeated for each adjoining pair of subperiods (2 and 3, 3 and 4, 4 and 5, 5 and 6). Demands and sorties were aggregated over longer times and correlations computed. None of the correlations was close to being significant, implying that high (or low) demand rates do not persist on an aircraft.[1]

- The correlation of the number of sorties flown in subperiods 1 and 2 was computed across the 39 aircraft. This procedure was repeated for the other adjoining subperiods. The object was to see whether those aircraft with greater utilization in one subperiod tended to have greater utilization in other subperiods. Since there is an attempt to utilize all aircraft and avoid permanent "hangar queens," we were not surprised to find that none of the correlations was close to being significant. High (or low) utilization rates do not persist on an aircraft.

- The correlation of demand rate and number of sorties was computed across the 39 aircraft. In order to avoid spurious correlations due to demand rates being computed from a single sortie, demand rates and sorties were summed for periods 1 and 2, 3 and 4, 5 and 6, 1 through 3, 4 through 6, and 1 through 6. For each of these six combination periods, we computed the correlation between demand rate and number of sorties. Only the first two correlations were statistically significant, with low demand rates associated with larger numbers of sorties. However, these correlations were dramatically affected by anomalous situations involving the same two tail numbers discussed in the footnote. In the first case, if the demand rates of 1.43 arising from 21 sorties by tail number 8503 and 1.33 arising from 15 sorties by tail number 8541 are replaced by the average demand rate of 0.56, the significance of the correlation between demand rate and sorties in the sum of periods 1 and 2 disappears. In the second case, if the demand rate of 2.25 arising from 4 sorties by tail number 8529 is replaced by the average demand rate of 0.56, the significance of the correlation between demand rate and sorties in the sum of periods 3 and 4 disappears.

Although there appears to be some relationship between lower demand rates and higher utilization, it is not significant in these data sets. As noted in the

[1] The correlation between subperiods 1 and 2 was significant because of a single data point, the demand rate of 3.00 in subperiod 1 for tail number 8503, arising from a single sortie. This happened to coincide with a large demand rate of 1.35 in subperiod 2 for that tail number. Since demand rates computed from a single sortie are extremely variable, this high correlation is spurious. If the value of 3.00 is replaced by the average demand rate for all aircraft of 0.66, or if rank correlations are used instead, the correlations become non-significant. A similar problem occurred in the correlation between subperiods 3 and 4 as a result of a single sortie by aircraft 8529. Here a rate of 4.00 in subperiod 3 happened to coincide with a value of 1.67 in subperiod 4. Again we deem this correlation spurious.

previous section, even if there were a significant relationship, we could not be sure that higher utilization causes lower demand rates.

In summary, all of our findings in this section are negative. Of course, these data pertain only to the F-15C/D1s at Kadena during 8 months of 1993. It is possible that other data sets could produce significant relationships, although we have performed several of these analyses on other data sets and have found no significant relationships.

Demand by Work Unit Code

Master Sergeant Mitchell and several associates at Langley attempted to classify WUCs into those thought to be driven by flying hours, those thought to be driven by sorties, and those unknown. Table 11-3 shows their split of WUCs into those three groups and the number of demands observed for each WUC. Overall, there were 3,366 demands in the Langley F-15C/D data, of which only 44 percent could be assigned to either flying hours or sorties. The number of demands was not used in making the classification but does give some idea of which WUCs are most important. Our hope was that demand for the flying-hour-driven group of WUCs would show a greater dependence on flying hours. In fact, when analyzed, the flying-hour-driven group showed even less dependence on flying hours than did the sortie-driven group.

We performed a second analysis using the F-16C worldwide data from Chapter 4. For each of the six two-digit WUCs with the largest amount of demand in the 1994 data, we broke the data into two groups comprising the first 108 days of 1994 and the next 105 days. (The purpose of having two periods was to have some idea of the stability of the slopes.) We then calculated slopes both before and after the adjustment for earlier/last sortie. The results are shown in Table 11-4.

It is comforting that the landing gear, which had the largest demand rate, showed no relationship with sortie length in either of the two periods. The only systems that did show a significant positive relationship were fire control and electronic warfare systems (EWSs), neither of which was assigned to the flying hour or the sortie group in Table 11-3 by Sergeant Mitchell. We note that the slopes for those two systems were quite consistent for both periods. (The slopes for fire control after adjustment were 23 percent for the first period and 19 percent for the second; for EWS they were 33 percent and 29 percent.)

Unfortunately, the engine WUCs accounted for only 1.4 percent of total demand in the 1994 F-16C data and thus did not constitute a large enough number of demands to analyze. The engine WUCs would have been an interesting group, because it is often hypothesized that their demands are more related to flying hours than is the case for most other WUCs. While there were 11 engine removals, there were a total of only 314 on-aircraft demands for the engine WUCs.

Table 11-3.
WUC Demands Assigned to Flying Hours or Sorties

WUC	System	Flying-hour-driven demands	Sortie-driven demands	Other or unknown demands
11	Air frame	86	–	–
12 A,C	Cockpit	18	–	–
12 E	Egress	–	–	7
13	Landing gear	–	407	–
14	Flight control	111	–	–
23	Engines	290	–	–
24 A,C,D	Auxiliary power	–	60	–
24 B,E	Auxiliary power	44	–	–
41	ECS	85	–	–
42 A,D,E	Electrical	49	–	–
42 B,C,F,Q	Electrical	–	18	–
44	Lighting	117	–	–
45	Hydraulic	76	–	–
46 A,B	Fuel delivery	42	–	–
46 D	Air refueling	–	–	3
46 E,F	Fuel indicator	44	–	–
47	LOX	29	–	–
49	Miscellaneous utilities	–	–	25
51	Instruments	–	–	221
52	Auto pilot	–	–	38
55	Malfunction	–	–	56
57	F/C guidance	–	–	5
63	UHF communications	–	–	175
65	IFF	–	–	121
71	Radio navigation	–	–	159
74	Fire control	–	–	719
75	Weapons	–	–	82
76	EWS	–	–	217
82	RMR	–	0	–
91	Emergency equipment	–	–	20
97	Explosive devices	–	–	42
Total		991	485	1,890

Table 11-4.
WUC Slopes for 1994 F-16C Worldwide

WUC	System	Demand rates	Before adjustment for sortie number (percent)	After adjustment for sortie number (percent)
13	Landing gear	0.06	0	0
		0.08	0	0
14	Flight control	0.01	12	7
		0.01	4	2
42	Electrical	0.01	19	13
		0.01	0	0
74	Fire control	0.05	29*	23*
		0.05	21*	19*
75	Weapons	0.02	15	7
		0.02	0	0
76	EWS	0.01	41*	33*
		0.01	32*	29*

* Statistically significant at 95 percent level.

Demand by Work Unit Code — 1995 F-16C Data

Using the 1995 F-16C data, we performed another analysis by WUC using slightly different methods. First, we picked out the six two-digit-level WUCs with the largest number of maintenance actions. These were the same six that had the largest number of maintenance actions in the 1994 data. Then the data were analyzed separately for each of two groups: regular Air Force bases, and AFR/ANG bases. We noted in the analyses of the F-16C, A-10, and HC-130P that the demand rates are typically lower at the AFR/ANG bases, and failure to analyze the data by homogeneous groupings can lead to spurious, higher slopes. The data in Table 11-5 are comprised of 32,747 regular Air Force sorties and 27,419 AFR/ANG sorties. Only training missions between 0.9 and 2.5 hours are included.

Even though our analysis methods for the 1995 WUC data were rather different from those used on the 1994 data in the previous section, the results are surprisingly consistent. The same two WUCs have the only significant slopes and the slopes themselves are nearly identical. After adjustment for sortie number, fire control had slopes of 21 percent and 24 percent in 1994 and 1995, respectively; EWS had slopes of 31 percent and 33 percent, respectively.

Table 11-5.
WUC Slopes for 1995 F-16C Worldwide

WUC	System	Demand rates	AFR/ANG demand rates	Before adjustment for sortie number (percent)	After adjustment for sortie number (percent)
13	Landing gear	0.08	0.06	0	0
14	Flight control	0.01	0.01	20	15
42	Electrical	0.01	0.01	2	0
74	Fire control	0.06	0.05	30*	24*
75	Weapons	0.01	0.01	0	0
76	EWS	0.01	0.01	42*	33*

*Statistically significant at 95 percent level.

Demand by Work Unit Code — 1995 F-15C/D Data

Because of the surprising consistency of our WUC results for the F-16C in two different years and the importance of tactical fighters, we decided to do a WUC analysis for another tactical fighter. The F-15C/D for 1995 was selected, because it had the largest set of data — over 20,000 training sorties with sortie durations in the 0.9- to 4-hour range. Another advantage of analyzing the F-15C/D is that the demand rates are higher.

In Table 11-6, the seven WUCs with the largest number of demands are displayed. Landing gear, fire control, and EWS were members of the largest WUCs for the F-16C as well. As in the F-16C cases of the previous two sections, we are pleased to see that the landing gear shows no dependence on sortie duration, and the only two WUCs with statistically significant slopes are fire control and EWS. Amazingly, the F-15C/D slopes for these two WUCs, both before and after adjustment for earlier/last sortie, are similar to those for the F-16C.

It was suggested that fire control and EWS might not be utilized on short sorties, and this might account for the large slopes. However, there are positive fire control demand rates of 0.076, 0.067, 0.077, and 0.078 even for the shortest sortie durations of 0.9, 1.0, 1.1, and 1.2 hours, respectively; positive EWS demand rates of 0.024, 0.032, 0.036, and 0.036 for the same sortie durations.

We believe that further detailed investigation of these two WUCs should be performed to identify causal factors that may explain the basis for a greater relationship to flying hours than is found with other WUCs. On the other hand, the slopes are still less than 50 percent, where flying hours and sorties would have an equal impact on demand.

Table 11-6.
WUC Slopes for 1995 F-15C/D Worldwide

WUC	System	Demand rates	Before adjustment for sortie number (percent)	After adjustment for sortie number (percent)
13	Landing gear	0.065	0	0
23	Engines	0.048	0	0
51	Instruments	0.024	0	0
63	UHF communication	0.027	16	12
71	Radio navigation	0.025	14	10
74	Fire control	0.083	26*	19*
76	EWS	0.039	34*	22*

*Statistically significant at 95 percent level.

Demand by Work Unit Code — HH-60G Helicopter Data

The largest number of demands for helicopters occurred in the HH-60G REMIS data. Since the 8,426 training sorties were a reasonably large number as well, we attempted to do some analyses by WUC. We expected that the results might vary from those obtained for the F-15C/D and F-16C above because helicopters are different. Indeed the two WUCs with the largest number of demands were 15 (rotor) and 51 (instruments), neither of which were prominent in the other analyses.

The demand rate was 0.04 for rotor and 0.03 for instruments. The slopes for both WUCs were nonpositive both before and after adjustment for earlier/last sortie of the day.

Deferred Maintenance Versus Grounding Breaks

When aircraft fly multiple sorties during a day, the demand rates after the last sortie are about three times greater than those following the earlier sorties. In this section, we examine whether the higher demand rates after the last of multiple sorties are due primarily to maintenance deferred from earlier sorties during the day or to maintenance requirements generated during that final sortie that were so extensive that no further sorties could be flown on that day. This is important because it determines whether the variable for earlier versus last of multiple sorties should be included in the regression results. If the difference in demand rates is attributable mostly to deferred maintenance, then this variable

should be included because some maintenance following the last sortie is not directly attributable to it; if the difference results mostly from aircraft with grounding breaks, then the maintenance following the final sortie is largely attributable to that sortie and no sortie variable is needed.

In addition, the last of multiple sorties tends to be slightly longer than earlier sorties during the day (e.g., 1.33 versus 1.31 hours for the F-16C, 1.39 versus 1.34 hours for the F-15C/D). Consequently, the slope of demand versus sortie length is usually reduced when the earlier/last sortie variable is included in the analysis. Over all aircraft types in Table 10-1, the earlier/last sortie variable reduces the average slope from 12 percent to 7 percent.

If we had good information about the sorties scheduled for each aircraft versus those flown, it could help determine how often grounding breaks caused further sorties to be canceled. We did have schedule information in the 1993 CAMS data set for the F-15C/D at Langley. However, there was a tremendous amount of aircraft substitution — between a third and half of the sorties. We were told that the policy then in force was to assign aircraft to missions without regard to the original assignments of tail numbers. Since it is not credible to believe that a third to half of the sorties result in grounding breaks, and since REMIS did not provide schedule information for the other data sets, we had to devise another method.

Our analysis plan was to examine the demand rates for the last sortie as a function of how many sorties were flown earlier in the day by the same aircraft. If demand is deferred from earlier sorties, we would expect the demand rate on the last sortie to increase with the number of earlier sorties; on the other hand, if demand arises solely from the immediately preceding sortie, then the demand rate following the last sortie should not be affected by the number of earlier sorties.

We use the 1994 data on the F-16C aircraft from the REMIS worldwide database in Chapter 4 because of the large number of sorties. Table 11-7 is a breakout of the data for the 23,178 last of multiple sorties of the day from Table 4-11. Since we are examining only cases with multiple sorties during a day, the number of sorties in a day by an aircraft starts with 2. Note that the number of demands per sortie on the last sortie of the day, shown in the last column, increases dramatically even though the average length of the last sortie is decreasing substantially.

Table 11-7.
Impact of Sortie Number on Demand

Number of sorties in a day by an aircraft	Number of days	Average length of last sortie (hours)	Demands/sortie on last sortie
2	18,747	1.34	0.33
3	3,354	1.30	0.42
4	898	1.28	0.39
5	169	1.19	0.44
6	10	0.86	0.60
Total/average	23,178	1.33	0.35

Although the number of days with large numbers of sorties is small, the increasing demand rates on the last sortie are statistically significant, with an average increase of 0.06 demands for each additional sortie. Thus, we conclude that the variable for earlier/last sortie of multiple sorties should be included, because there is a substantial amount of deferred maintenance.

Further confirmation of deferred maintenance is provided by the Langley F-15C/Ds in Table 4-3 and the C-141 and C-5. In each case demand was substantially higher when the aircraft returned to its home base.

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APPENDIX A

On a Controlled Experiment

On a Controlled Experiment

Introduction

In this report's Chapter 1, we explored some of the advantages of a controlled experiment. Here we provide a hypothetical example of what could happen in the absence of such an experiment. When the same data are aggregated in two different ways, we get contradictory results. This phenomenon is known in the literature as Simpson's Paradox.

Simpson's Paradox

Suppose that we have 100 tactical aircraft. We separate them randomly into two groups of 50 aircraft each and administer some experimental treatment to one group while the other is used as a control. The experimental treatment could be a change in maintenance procedures or a new type of operational mission. Furthermore, we attempt to control for extraneous sources of variation by assigning each pilot to one mission from the control group and to one mission from the experimental group, by ensuring that sortie lengths are about the same, etc.

Each aircraft flies one sortie, and we compare the number of aircraft that require unscheduled maintenance (number broken) as the measure of effectiveness. Table A-1 is an example of what the results might look like.

Table A-1.
Simpson's Paradox

Group	Total number of aircraft	Number of broken aircraft	Percentage broken
Control	50	22	44
Experimental	50	28	56

Our initial reaction would be to reject the experimental treatment, since it results in a higher percentage of broken aircraft. But then some smart analyst realizes that we have not controlled for all sources of extraneous variation. He notes that half of the aircraft are a new model, and he breaks the data in Table A-1 down into two subtables.

Now the experimental treatment looks better than the controls in each group of old and new aircraft. Note that the number of aircraft broken in the two control groups of Table A-2 (8 and 14) add to the total in Table A-1 (22); all other data in Table A-2 must add up to the values in Table A-1 as well.

Table A-2.
Simpson's Paradox Example by Aircraft Age

Group	Total number of aircraft	Number of broken aircraft	Percentage broken
Old aircraft control	40	14	35
Old aircraft experimental	10	2	20
New aircraft control	10	8	80
New aircraft experimental	40	26	65

What can we conclude from this experiment? The experimental treatment does not look good according to the aggregate data in Table A-1, but it does look encouraging according to the detailed data in Table A-2. We might be tempted to test the data in each table for statistical significance using a chi-squared test — with the numbers above, the results are not statistically significant. On the other hand, if the experiment had used 10 times as many sorties leading to the results above, except that each value in the tables was multiplied by 10, the results in Tables A-1 and A-2 would each be highly significant — though contradictory!

It is tempting to conclude that the experimental treatment was better because it was better in each of the age groups of Table A.2. But we would be on much firmer ground if we had properly controlled for all sources of extraneous variation when the experiment was designed. The number of new aircraft assigned to the treatment group was too large because we did not control for aircraft age.

The moral of Simpson's Paradox is, of course, that experiments should be designed to control for all sources of extraneous variation. While it never hurts to control for variables that later turn out not to matter, failure to control for significant variables can invalidate the experiment.

APPENDIX B

Effect of Data Combination on Regression Results

Effect of Data Combination on Regression Results

Introduction

Three different procedures can be used on the raw sortie data before regression analysis is employed:

- The individual sortie data can be used.
- The sorties at each specific duration can be aggregated and the average demand rate used for that number of sorties.
- The sorties at each specific duration can be aggregated and the average demand rate used in a weighted regression where the weights are the number of sorties.

The second and third procedures reduce the variability in the raw data; if there are 10 sorties of a particular duration, the second procedure will use the average demand for the 10 sorties on each of the 10 observations, whereas the third procedure will use the average as a single observation but weight it by 10.[1]

In a simple regression with demand as the dependent variable and sortie length as the independent variable, all three procedures yield the same regression equation. However, the percentage of variance explained by regression, known as the R^2, can vary dramatically. It is smallest under the first procedure. Usually the R^2 is larger for the second procedure than for the third, but this depends on the number of data points.

More important, the statistical significance of the regression line, as measured by the t statistic, behaves similarly to that of the R^2. A slope that is nonsignificant under the first procedure can appear to be highly significant statistically under the others. These statements are proven in the next section for the first and second procedures.

In most of the analyses done by the U.S. Air Force and others prior to 1980, the several sorties at each specific sortie duration were combined using the second or third procedure. In our analyses in this report, we had to use the first procedure, because we wanted to use more than one independent variable in

[1] At first glance, the second and third procedures appear to be identical. However, as the number of data points increases, the statistical significance of the regression coefficients increase under the second procedure. In the weighted regression of the third procedure, the weights are the relative importance of the squared errors at each sortie duration. When the weights are multiplied by any constant, the R^2 and the statistical significance of the regression coefficients are unchanged.

multiple regressions (e.g., mission type, earlier versus last of multiple sorties during a day, deployment from the home base, deployment to the home base). It is not possible to aggregate all sorties of a given duration, because the sorties differ with regard to these other variables. Since the various R^2 in our analysis are not comparable with those of earlier analyses, we have not presented them.

However, the first procedure should be used even if simple regression is the only analysis technique used. Any sort of aggregation in which the raw data are replaced by averages will increase the apparent statistical significance. Taking aggregation to an absurd extreme, we could aggregate all the data into one group of short sorties and one group of long sorties, using the average demand and sortie duration for each of the two groups. Applying the second procedure where the values for each group are repeated for the number of sorties, the result from any set of data would be an R^2 of 100 percent and significant coefficients for the regression.

Regression Analysis

The combination of data that we consider is one in which there are several observations, Y, at a given X value (e.g., the observations, Y, are the number of demands on a sortie and the X values are the sortie duration). We suppose that all observations, Y, at each particular X are averaged before regression is employed.

Proof that Regression Coefficients Are Unaffected

Consider the regression

$$Y = A + BX.$$

The least squares estimate of B is

$$B = \frac{\Sigma X_i Y_i - \Sigma X_i \Sigma Y_i / N}{\Sigma X_i^2 - (\Sigma X_i)^2 / N},$$

where N is the number of data points. The summation of Y in the second term of the numerator is unaffected by a prior averaging of Y at a particular value of X, and the first term is unaffected because Ys that are averaged are multiplied by the same value of X. Thus the regression estimate, B, is unaffected by the averaging.

The least squares estimate of A is

$$A = \Sigma Y_i / N$$

and this is clearly unaffected by a prior averaging of the Ys at a particular value of X.

Correlation Coefficient

The correlation coefficient is estimated by

$$r = \frac{\Sigma X_i Y_i - \Sigma X_i \Sigma Y_i / N}{(N-1) S_x S_y}.$$

Since the numerator is the same as the estimate for B, it is unchanged by averaging the Y values for a given X. S_x is the standard deviation of the Xs and this is unchanged; however, S_y is the standard deviation of the Ys and this has been reduced by the averaging of the Y values at a given X. Thus, the correlation coefficient is inflated by the averaging process.

Standard Error of Estimate for Coefficients

The standard error of estimate for the coefficients (the confidence interval) is proportional to where

$$S_{yx}^2 = \frac{N-1}{N-2}(S_y^2 - B^2 S_x^2).$$

Note that the only quantity affected by the combination is S_y which is reduced, making each coefficient appear to be more significant.

APPENDIX C

Evaluation of Past Research Studies

Evaluation of Past Research Studies

Introduction

The major studies are reviewed in alphabetical order. Our reviews are headed by the title, date, and author and by a description of the data. The findings and limitations are then summarized, and an evaluation of the study is given.

Boeing (January 1975 and 1962)

Title: *Reliability Developments — AWACS* (1975)

Author: E. J. Peacore, Boeing

Data: B-52 radar failure.

Title: *Determination and Use of Failure Patterns* (1962)

Author: R. L. Horn and G. S. Shoup, Boeing

Data: B-52 aircraft failures.

These two studies are reviewed together because they deal with the same aircraft, and the 1975 study is partially based on the 1962 one.

Findings

Failure rate is not constant throughout a mission. Most failures are caused by infrequently failing parts.

The 1962 study fits Weibull distributions to the failure rates by subsystem. A value of 1 for the Weibull shape parameter is appropriate for a constant failure rate (i.e., where demands are a linear function of sortie duration); a value of 0 would indicate that all failures are sortie related. The fitted failure rates for the aircraft as a whole are 0.156 (range by subsystem from 0.083 to 0.567), indicating that the sortie effect is much more important than the flying-hour effect.

The 1975 study consists of data from a B-52 radar in two field tests. The amount of data is much more limited, but the constant failure rate model is again rejected. The authors fit a Duane curve instead of a Weibull, but the concepts are similar.

Limitations

Most of the data are over 30 years old (1962 study), and they pertain to only one aircraft type. The sortie duration effects are pronounced, partly because some of the sortie durations are as long as 24 hours. Thus, the applicability to current tactical aircraft is limited. However, if this experience is extrapolated to tactical aircraft, it would be expected that the demands during a 2-hour sortie would be increased only 10 percent by increasing the sortie to a 5-hour duration.

Evaluation

The 1975 study is concerned with the time until the radar fails during an 8-hour mission. There is a maximum of one failure, making these data dissimilar to studies that measure the total number of failures during a specified period. Consequently, the appropriate curve for the constant failure case is not a straight line but an exponential function.

For that reason, the quantitative results are somewhat different in these two studies, but the qualitative result for both is that failure rates decrease with mission duration.

CORONET EAGLE (JANUARY 1981)

Title: *Final Report on the Coronet Eagle F-15A/B Deployment*

Author: Headquarters Tactical Air Command, Langley AFB

Data: The exercise was conducted from 2 October to 5 November 1980 using 18 aircraft to demonstrate ability to deploy to Europe and simulate combat conditions. There were 1,001 sorties in 20 flying days and a 3.0 sortie rate during the 18 days of simulated combat. Average sortie duration was 0.9 hours versus the home station average of 1.22.

Findings

Mission-capable rates were higher during the exercise — 79.4 percent versus 69.3 percent at home station. Break rates were 7.1 percent versus 12.5 percent at the home base. The highest proportion of breaks were on the first and fourth sortie waves (8.3 percent and 11.5 percent, respectively).

Readiness spares kits had 95.1 percent of the 3,702 units authorized. During the exercise, 455 units were issued (343 for AC, 14 for AGE repair, and 98 for avionics test stand repair), which was a 72.8 percent fill rate. There were 223 units requested via lateral resupply from Bitburg, Germany, of which 170 were

obtained. Also, there were 7.4 cannibalizations per 100 sorties versus 34.0 per 100 at the home station.

Donaldson, T. S., and A. F. Sweetland, The RAND Corporation (August 1968)

Title: *The Relationship of Flight-Line Maintenance Man-Hours to Aircraft Flying-Hours*

Data: B-52, F-100, F-102, F-4C (two samples), F-5A, and C-130 using Air Force Manual (AFM) 66-1 data, augmented to enable all flight-line maintenance hours to be assigned to the appropriate aircraft and sortie.

Findings

Unscheduled flight-line man-hours are at best only slightly related to flying hours. For most aircraft, there was a very slight increase in man-hours as sortie lengths increased, though there was a decrease for the F-5A due probably to mission differences. Only the C-130 showed a fairly constant MH/FH relationship, but only for those missions that fly multiple sorties between maintenance stops.

All maintenance measures were highly correlated with each other — maintenance man-hours, net aircraft recovery time, and number of WUC write-ups. These write-ups were always more highly correlated with flying hours, but the absolute difference was small.

Attempts to find relationships between flying hours and maintenance hours by shop were unsuccessful (F-102 sample).

Limitations

It was not possible to collect shop and depot maintenance data and assign them to the aircraft and sortie that generated the maintenance.

There may be some interaction with maintenance initiated by scheduled inspections. If scheduled maintenance is successful, subsequent man-hours should decrease. There is evidence that remove-and-replace actions for inspections increase the probability of failure, and thus preventive maintenance may increase subsequent man-hour requirements.

Although there is variation in sortie length, the number of very short or very long sorties is always small, reducing the ability to make statistically significant inferences.

Evaluation

This is one of the most impressive, careful analyses of the relationship between flying hours and maintenance measures. Several aircraft types were used, and similar results were obtained. AFM 66-1 data were augmented to provide the link between maintenance and the specific aircraft and sortie. The statistical analysis was excellent.

The major problem with utilizing the results of this study is that the data are nearly 30 years old and most of the aircraft studied are no longer in service. Second, the data are maintenance data, not supply data, and there may be some important differences. Finally, there was only limited variation in the sortie lengths, and none of the studies was conducted as a controlled experiment.

HOWELL, L. D., AF/ASD (AUGUST 1978)

Title: *A Method for Adjusting Maintenance Forecasts to Account for Planned Aircraft Sortie Lengths* (Technical Report ASD-TR-78-26)

Data: C-130E, C-141A, 727, and B-52D maintenance actions.

Findings

The Howell analyses for the C-130 and C-141 are the most detailed, so we will dwell on them rather than on those for the B-52D and Boeing 727. Howell performs separate regressions for 20 WUCs to determine the intercept and slope for the number of maintenance actions per sortie as a function of sortie length for June 1976 through September 1976 and for October 1976 through May 1977.

The results for a given WUC tend to be very different for the two periods. If the results are meaningful, the relationships for a given WUC should be similar. In the first period regressions for the C-130, most of the intercept values are statistically significant, as are about half of the slopes; these results are reversed in the second period.

For the C-141, most of the coefficients are not statistically significant in either period for either the intercept or the slope.

The results for a given WUC over the entire period are statistically significant for most intercepts and for all but five slopes for the C-130, and they are significant for most slopes but for only five intercepts for the C-141.

The results for all maintenance actions on the C-130 over the entire period are statistically significant. The intercept of 1.617 and slope of 0.605 indicate that maintenance is more related to the number of sorties rather than to their length.

The results for all maintenance actions on the C-141 over the entire period are statistically significant only for the slope of 0.919. The intercept of – 0.2 is not significantly different from zero statistically, suggesting that maintenance actions are a linear function of flying hours only.

The base-to-base differences overwhelm the differences due to sortie length. For example, for the C-130, the following data were reported at 9 bases; we have sorted them by the number of maintenance actions per sortie (see Table C-1).

Table C-1.
C-130 Experience

Location	Number of aircraft	Maintenance actions/sortie	Flying hours/ month/aircraft	Sorties/month/ aircraft	Average sortie duration (hours)
Langley	6	4.78	45.33	19.23	2.36
Pope	38	4.04	51.44	19.57	2.65
Rhein Main	15	3.91	51.64	19.73	2.62
Clark	18	3.86	51.30	18.38	2.79
McCord	21	3.57	50.42	15.94	3.16
Little Rock	64	3.13	53.62	16.44	3.26
Mendenhal	16	2.85	55.42	18.71	2.96
Elmendorf	10	2.66	48.42	25.09	1.95
Yokota	18	2.53	52.87	19.47	2.72
Correlation			– 0.58	– 0.25	– 0.08

Note that the maintenance actions per sortie vary by a factor of almost 2 to 1, a variation far greater than the one in flying hours or sorties. Although the variation in average sortie duration is almost 2 to 1, there is no relationship between maintenance actions and sortie duration (correlation coefficient of – 0.08). There is no obvious relationship between maintenance actions and either base location or number of aircraft possessed.

The negative correlations between maintenance and flying hours (sorties) do make some sense in that higher utilization is thought to result in fewer maintenance actions per sortie or per hour. However, the small differences in average hours or average sorties cannot possibly account for the huge maintenance differences. This is even more clear when we review the evidence for the C-141 (see Table C-2).

Table C-2.
C-141 Experience

Location	Number of aircraft	Maintenance account/sortie	Flying hours/ month/aircraft	Sorties/month/ aircraft	Average sortie duration (hours)
McGuire	47	4.08	64.15	19.70	3.26
Travis	41	3.65	55.17	13.37	4.13
Charleston	49	3.26	58.45	16.39	3.57
Norton	50	2.65	24.64	5.90	4.17
McCord	40	2.65	38.78	13.75	2.82
Correlation			0.89	0.75	0.03

We eliminated from the table above, the data for 16 aircraft at Altus, OK, which had an average of 9.5 maintenance actions per sortie. It is clearly not appropriate to include them in the same group, because the behavior is markedly different. However, Howell did include the Altus data in his analysis and, in doing so, may have significantly degraded his results.

The C-141 data are similar to those for the C-130 in that there is a fairly large range of maintenance actions per sortie that cannot be explained by the small changes in flying hours or sorties. Note that these first two correlations are large as with the C-130, but that the sign is positive, suggesting that aircraft that are utilized more intensively tend to have more maintenance per sortie.

Evaluation

Overall, our conclusion is that the base-to-base differences appear to be much more significant in their effect on maintenance than are any factors concerning the flying program. This phenomenon may be due to aircraft age or other factors not specifically related to location, since these transport aircraft fly all over the world. All in all, these studies tend to support the desirability of a controlled experiment in which external variation is balanced and data are collected prospectively rather than retrospectively.

APPENDIX D

CAMS Data Call

CAMS Data Call

Study Objective

Our objective is to extract from the Core Automated Maintenance System (CAMS) data those transactions that most closely represent spares demand and to relate those demands to the sorties on which the demands arose (using the CAMS Daily Report of sorties by tail number). For this purpose, we need three types of CAMS records covering the same period of time and group of aircraft: (1) the maintenance history; (2) the Daily Report of flying activity; and (3) the Daily Report of sorties scheduled by tail number, those actually flown, and the takeoff and landing location codes and times.

Maintenance History

The maintenance history records of interest are those that relate to on-aircraft remove and replace, excluding aircraft servicing, time change technical orders (TCTOs), time change items, and off-equipment maintenance. When the maintenance history record is run from CAMS, it appears that the following option switches should be used to minimize the amount of data:

Type Report	On-Equipment Only	(Option 1)
WUC Codes 01 – 09	N	
WUC Code TCTO	N	
Action taken	P/ Q/ R	
Report Sequence	E (Equipment)	

The data elements we need are

- tail number,
- Event-ID (which includes the date),
- WUC,
- Action Taken code,
- When Discovered code,
- How Malfunctioned code,

- units produced,
- start time, and
- sortie number.

The usual man-hour reports include all this information. It is critical that the information contains all of these data elements; if there are additional ones, we can easily eliminate them from the data provided.

Daily Report of Flying Activity

The flying activity is usually provided in aircraft utilization reports (AURs), of which the Daily Report of flying accomplished is the most important. The data elements that we need for sorties actually flown are

- tail number,
- date,
- sortie number (3-digit code),
- actual start time,
- actual stop time,
- sortie duration (in tenths of an hour), and
- mission type (4-position alphanumeric).

Please note that we cannot use monthly summaries by tail number. It is critical that we have information on individual sorties by tail number. Usually the AUR includes information on aborts, cancellations, etc., that we would like also.

Planned and Actual Sorties and Locations

Data in CAMS give, by tail number, the planned and actual sorties by date. For those tail numbers that actually flew a sortie, there is information on

- tail number,
- date,
- scheduled takeoff date and time,

- scheduled landing date and time,
- actual takeoff date and time,
- actual landing date and time,
- number of sorties,
- starting location (4-position alphanumeric), and
- ending location (4-position alphanumeric).

The data have been extracted for us by the Langley F-15 CAMS people by using the Query Language Processor code that follows. These are SUD-202 records extracted from the Equipment Inventory, Multiple Status, and Utilization Reporting Systems of CAMS.

- Must be in the Exec Mode of Demand
- @BK1
- INVOKE FS-QLP1-5R! DMS$XXXX*CAMSDBG-5R1 (X=YOUR ALN #)
- LIST SUD-202 WHERE SUD-KEY MASK-**************='A'
- @BK2 NTR00P (00=YOUR NTR NUMBER)

Appendix E

Glossary

Glossary

AFB	=	Air Force Base
AFM	=	Air Force Manual
AFR	=	Air Force Reserve
ANG	=	Air National Guard
AOR	=	area of responsibility
AUR	=	aircraft utilization report
CAMS	=	Core Automated Maintenance System
CONUS	=	Continental United States
EWS	=	electronic warfare system
FH	=	flying hour
MDS	=	Mission Design Series
MH	=	maintenance hour
MTBF	=	mean time between failures
OH	=	operating hour
REMIS	=	Reliability and Maintainability Information System
SBSS	=	Standard Base Supply System
SOF	=	Special Operations Forces
TCTO	=	time change technical order
USAF	=	U.S. Air Force
USAFE	=	U.S. Air Force, Europe
WMP-5	=	*War and Mobilization Plan*, Volume 5
WUC	=	work unit code

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In Operation Desert Shield/Desert Storm, while tactical aircraft flew much longer sorties than planned, the demand for aircraft spares was substantially less than expected. The war plans were based on the standard assumption that spares demand is proportional to flying hours. Since wartime demand is predicted from peacetime data, and the peacetime training missions are mostly short sorties, it is critical to know whether spares demand is driven by the number of sorties, by flying hours, or by some combination. The U.S. Air Force has now accepted the results of our analysis, which show that demand is much more closely related to the number of sorties than it is to the number of flying hours. We recommended that the Air Force use a slope of about 10 percent, meaning that for each additional hour of sortie length after the initial hour, demands increase 10 percent. The data comprise over 700,000 sorties for 24 major aircraft types. The analysis controlled for a number of explanatory variables, including deferred maintenance, mission type, and location, as well as sortie length.

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